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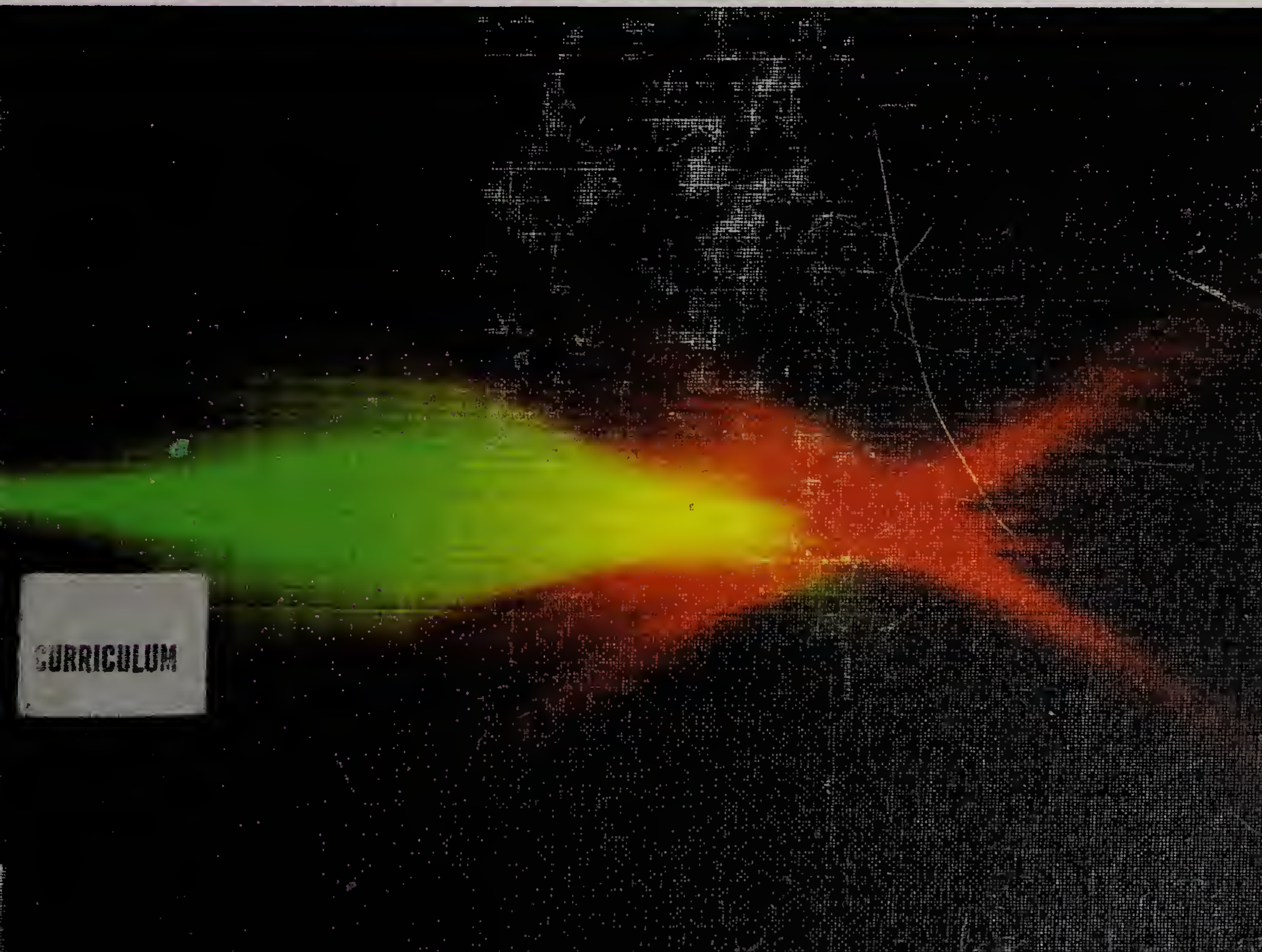

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COVER

The cover photograph is a recording of a new lens test to examine chromatic aberration. The lens used was an experimental lens with a large amount of chromatic aberration, but a small amount of monochromatic aberration. The photograph shows a greatly magnified side view of the distribution of white-light energy as it comes to the focus of the experimental lens. The view is perpendicular to the optical axis of the lens.

The picture can be thought of as generated by moving a white thread (white light) along the optical axis being photographed from the side. The picture is, therefore, a composite of all positions of the thread. (*Photo, courtesy of Itek Corporation, Lexington, Massachusetts.*)

Frontiers of PHYSICS

Robert Stollberg · *Faith Fitch Hill*

Canadian Edition by
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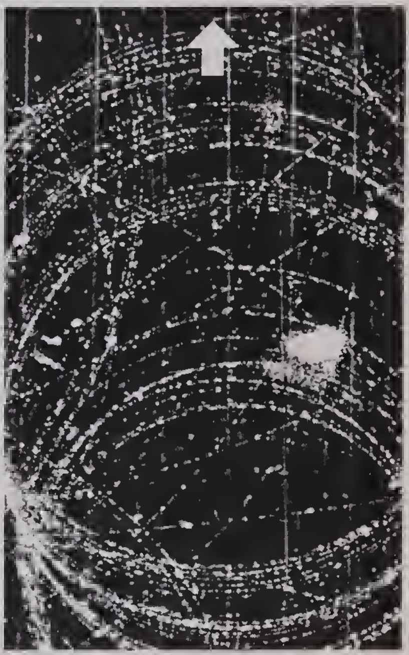
UNIT ONE

Force and Motion— Matter and Energy

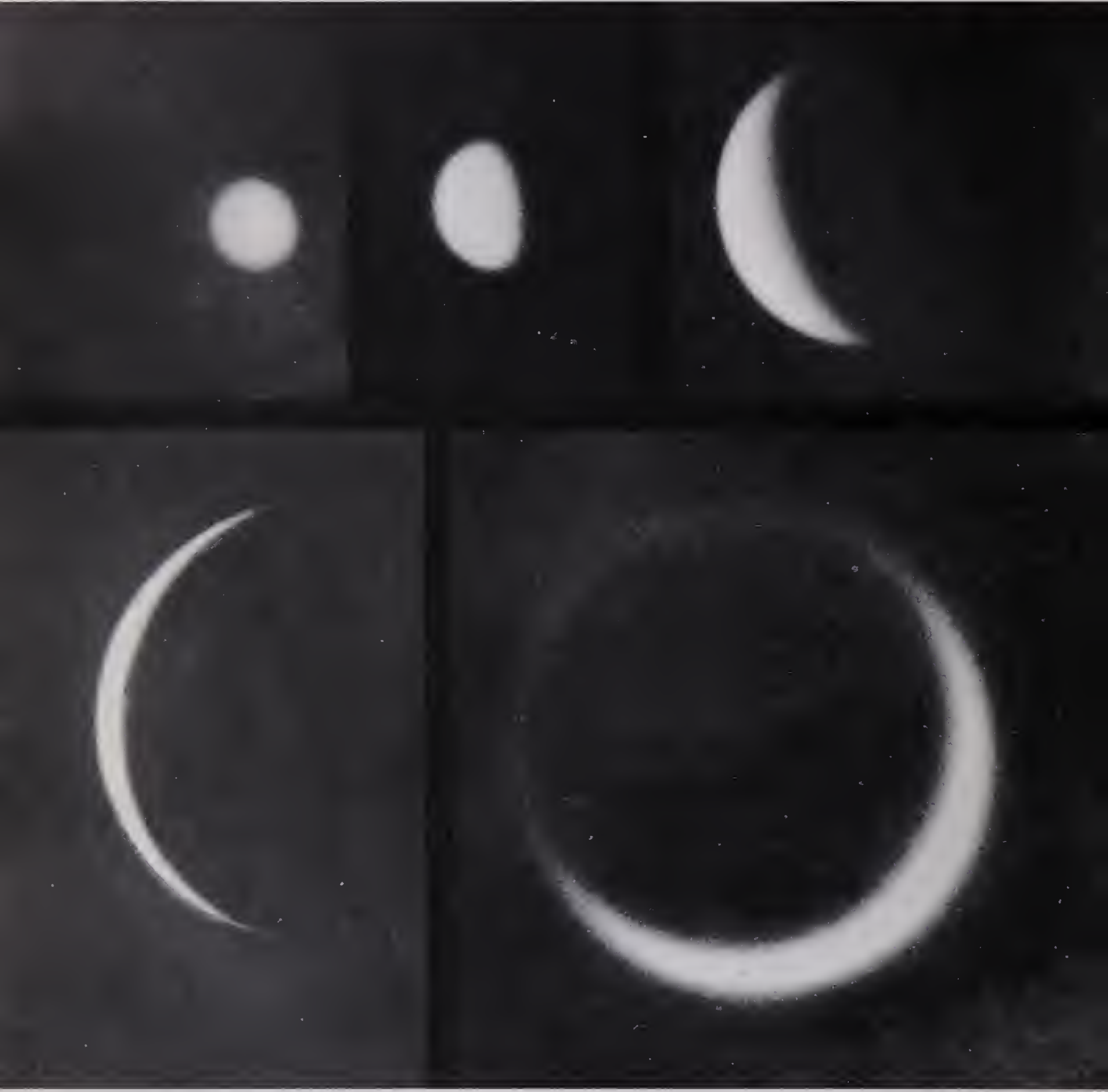
Courtesy of the National Maritime Museum, Greenwich, England and reproduced by permission of the Trustees.

Some problems of rocketry are being investigated in this 19th century etching.

This book begins with a consideration of the fundamentals of physics: how motions are analyzed, how forces are measured, how forces produce motions, and how they are related to matter and energy. Even on the frontiers of physics, in such areas as optics, nucleonics, and electronics, you never cease dealing with force and motion and their relationship to matter and energy. Unlike most physics books, this one includes an early introduction to the structure and behavior of the atomic nucleus so that you may early recognize that the concepts of force and motion relate to matter and energy. Such a development allows you to see the interrelationships of fundamental concepts and how these concepts form the basis for understanding complex physical phenomena.



CHAPTER 1



From photographs by E. C. Slipher, Lowell Observatory.

These photographs show the phases of Venus. In the crescent phases, Venus is closer to the earth and appears larger and brighter than at other times.

Motion and Measurement

Are you planning a trip to Venus (see facing page)? On some evening when Venus is very bright, it is a mere twenty-six million miles away. Now would seem to be a good time to start. Your rocket must have enough fuel to lift you off the earth and give you the necessary escape velocity of about 25,000 miles per hour. Soon you can cut off your rocket engine and coast the rest of the trip. You should reach the orbit of Venus in about 3 months.

But where is Venus? You headed straight for it, but now it is not there. If you look out into the sky, you will see it, not quite as bright as when you left the earth, for in 3 months it has moved about a hundred seventy million miles and is farther away than ever.

Perhaps you could have started earlier and aimed for the point where Venus will be when you arrive. In that case, you will need a very careful determination of the angle at which you leave the earth. If you make an error of only a tenth of one degree, you will miss your destination completely.

The engineers who plan the launching of satellites and rockets into outer space must know a great deal about motion, velocity, acceleration, and mathematics, so that they can make their calculations. When you finish reading this chapter, you will not be able to plot the course of a spaceship, but you will know a little bit more about motion and the way in which physicists handle their calculations.

Uniform Motion

1–1 Velocity is speed in a specified direction. Automobile speed records are often made on the salt flats of Utah. Here on the hard, level surface a driver can race without being slowed by bumps or sudden turns. When he has finished his course and the record has been calculated, no one asks whether he was going east or west or around in a huge circle.

Airplane speed records are somewhat different. If you were told that a plane covered the distance from coast to coast in a certain length of time, you might need to know whether the trip was east-to-west or west-to-east, before you could tell whether or not this was a record-breaking trip. Direction does matter in this case because west-to-east trips have the prevailing winds with them and therefore take less time than trips in the opposite direction.

When a physicist uses the term **velocity** (v), he is referring not only to how fast an object may be moving, but also to its direction. Velocity is a **vector quantity,** one that has both *magnitude* (amount) and *direction.* The magnitude of a velocity is termed its **speed,** which may also be defined as the distance traveled per unit time. A quantity, like speed, that has only magnitude is called a **scalar quantity.**

The length of a piece of paper may be 20 centimeters. The direction is not important because the paper may lie in any position. However, the distance from Calgary to Edmonton is not simply 180 miles; it is 180 miles in a direction from south to north. This latter distance is a vector quantity. A distance vector which is measured in a particular direction between two points is called a **displacement** (s).

If you push or pull on an object, you do so in a particular direction. Therefore the force (a push or a pull) is a vector quantity. As you read this book, you will become acquainted with other vector quantities.

Some quantities never are vectors. Try to imagine the direction of a quart of water, for example. Volume, the brightness of a light, the temperature of a room, the loudness of a sound, have magnitude but not direction. They are scalar quantities.

1–2 Uniform velocities can be calculated. A velocity is called a **uniform velocity** when there is no change in either the direction or the magnitude of the motion. The formula for uniform velocity tells mathematically that velocity is the displacement (s) in a given direction divided by the time (t) during which the displacement occurs.

$$v = \frac{s}{t}$$

In practice, velocities are seldom truly uniform for more than brief intervals of time. So a measurement of uniform velocity must be made in terms of a small displacement and a corresponding small interval of time. In mathematics, this is commonly expressed by using the Greek letter delta, Δ, to indicate a small change in some variable. Accordingly, the formula for velocity is often written:

$$v = \frac{\Delta s}{\Delta t}$$

You would read this, "v equals delta s over delta t." In your mind, however, you would think, "Velocity equals a small displacement divided by a corresponding small interval of time."

A car speedometer records only the magnitude of the velocity. If you watch the speedometer, you notice that the speed does not remain the same, but increases and decreases. Usually the direction also changes frequently. To find the magnitude of the average velocity, you can use the same formula as for uniform velocitv, writing v_{av} instead of v:

$$v_{av} = \frac{s}{t}$$

The direction of the average velocity and the direction of the displacement are the same. See Examples 1 and 2 on p. 3.

There are several points worth noting about Example 2. One is that no direction was given, since only the magnitude of the velocity was involved in the solution. Secondly, notice very carefully the way in which the units have been written into the solution, and the fact that they have been handled algebraically in the same way as

EXAMPLE 1

A plane flies 266 miles from Edmonton to Medicine Hat in a time of 1.75 hours on course 147°. (This means at an angle of 147° measured clockwise from true north). Find the average velocity.

Given: $s = 266$ mi.
$t = 1.75$ hr.
course $= 147°$

To find: v_{av}

$$v_{av} = \frac{s}{t}$$

Solution: $v_{av} = \frac{s}{t}$

$$v_{av} = \frac{266 \text{ mi.}}{1.75 \text{ hr.}}$$

$$= 152 \text{ mi/hr.}$$

$$v_{av} = 152 \text{ mi/hr. on course } 147°,$$
Answer

EXAMPLE 2

A jet plane can travel at an average rate of 600 mi/hr. How much time is required for it to travel from Vancouver, B.C., to Winnipeg, Manitoba, a distance of 1500 miles?

Given: $v_{av} = 600$ mi/hr. $s = 1500$ mi.
To find: t

$$v_{av} = \frac{s}{t}$$

Solution: $v_{av} = \frac{s}{t}$

$$600 \text{ mi/hr} = \frac{1500 \text{ mi}}{t}$$

$$\frac{600 \text{ mi} \times t}{\text{hr}} = 1500 \text{ mi.}$$

$$t = \frac{1500 \text{ mi} \times \text{hr}}{600 \text{ mi}}$$

$$t = 2.5 \text{ hr}$$

$$t = 2 \text{ hr} + 0.5 \text{ hr} \times \frac{60 \text{ min}}{1 \text{ hr}}$$

$t = 2$ hr 30 min, Answer

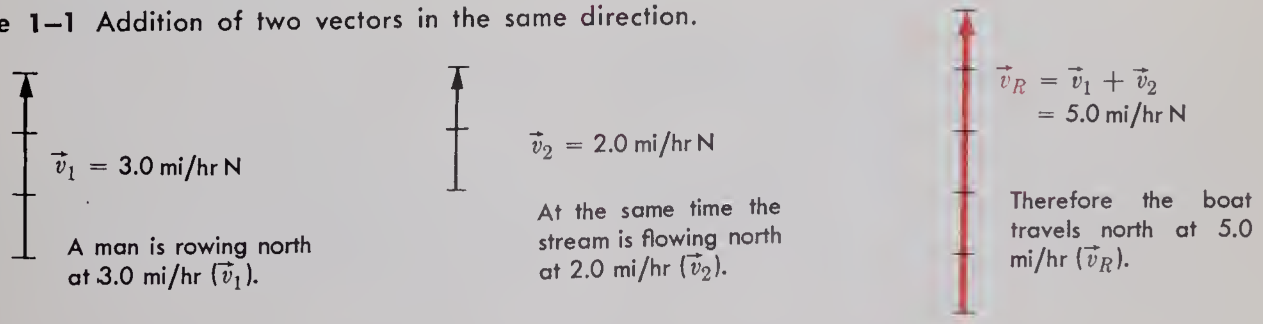
numbers. Finally, notice that the answer has been rounded off to three digits, since only three were given for the magnitude of the average velocity. You will learn about the rules for handling digits on pages 20–21.

1–3 Velocities may be represented by diagrams. Any vector quantity may be represented by an arrow in the proper direction, with its length proportional to the magnitude of the quantity. For example, suppose that a man is rowing a boat north at 3.0 mi/hr. At the same time the stream is flowing north at 2.0 mi/hr. These two quantities are diagramed in Fig. 1–1.

As a result of these two motions, the boat travels at a velocity of 5.0 mi/hr north, with respect to the bed of the river. This is called the resultant velocity (v_R) or, simply, the *resultant*. It is diagramed in the third part of Figure 1–1. The arrow above the letter v in these diagrams means that this is a vector quantity. The **resultant** of any group of vectors is the single vector that has the same effect.

Now the man turns and rows south at 3.0 mi/hr. However, the stream is carrying him north at 2.0 mi/hr. Therefore, the resultant velocity is 1.0 mi/hr south. The vector diagram is shown in Fig. 1–2. Notice

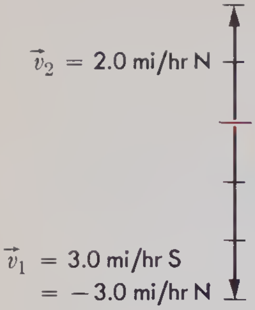
Figure 1–1 Addition of two vectors in the same direction.


$\vec{v}_1$ = 3.0 mi/hr N
$\vec{v}_2$ = 2.0 mi/hr N
$\vec{v}_R = \vec{v}_1 + \vec{v}_2$
= 5.0 mi/hr N

A man is rowing north at 3.0 mi/hr ($\vec{v}_1$).

At the same time the stream is flowing north at 2.0 mi/hr ($\vec{v}_2$).

Therefore the boat travels north at 5.0 mi/hr ($\vec{v}_R$).



$$\begin{aligned}\vec{v}_R &= \vec{v}_1 + \vec{v}_2\\ &= -3.0\ \text{mi/hr N} + 2.0\ \text{mi/hr N}\\ &= 1.0\ \text{mi/hr S}\end{aligned}$$

Figure 1–2 Addition of two vectors in opposite directions. Vectors toward the north are considered positive; and those toward the south, negative. The stream flows north. The man rows south. The resultant is a velocity of 1.0 mi/hr south.

that for both of these cases the resultant is the sum of the other two vectors with attention being paid to the direction of each vector. Because the resultant is the sum of two (or more) vectors, it is often called the **vector sum.**

Figure 1–3 shows more complicated situations. Here the man is rowing at an angle to the stream. In order to find the resultant, draw the two vectors to scale with the tails of the arrows touching and the proper angle between them. Then complete a parallelogram, using these vectors as two of the sides. The resultant is the diagonal of the parallelogram. Since the drawing is made to scale, the magnitude and direction of the resultant can be found by measurement.

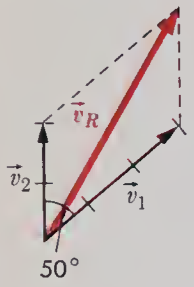
The equation for the resultant is:

$$\overrightarrow{v_R} = \overrightarrow{v_1} + \overrightarrow{v_2}$$

This equation shows that directions must be taken into account, which is not the case in ordinary addition.

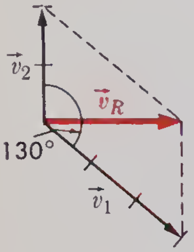
If the man in the boat rows at right angles to the stream, the resultant can be found from a scale drawing, but it can also be found by computation. Figure 1–4 shows two ways in which this can be done.

Figure 1–3 Addition of vectors at acute and oblique angles.



a. If the man rows at an acute angle (50° in this case) to the stream, the resultant velocity is found by completing a parallelogram, using v_1 and v_2 as two of the sides. Here the parallelogram has been drawn to scale and the resultant is found to be 4.5 mi/hr at an angle of 30° east of north.

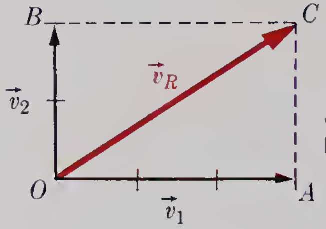
$$\vec{v}_R = \vec{v}_1 + \vec{v}_2 = 4.5\ \text{mi/hr at } 030°$$



b. This method works also if the angle between the vectors is oblique (130° here). By measuring the resultant, you can see that it is 2.3 mi/hr at an angle of 88° east of north.

$$\vec{v}_R = \vec{v}_1 + \vec{v}_2 = 2.3\ \text{mi/hr at } 088°$$

Figure 1–4 Addition of vectors at right angles to each other.



When the vectors are at right angles, the magnitude of v_R can be found by the Pythagorean theorem.

$$v_R^2 = v_1^2 + v_2^2$$ (no arrows because only magnitude is involved)

$$= \left(3.0\,\frac{\text{mi}}{\text{hr}}\right)^2 + \left(2.0\,\frac{\text{mi}}{\text{hr}}\right)^2$$

$$= 9.0\left(\frac{\text{mi}}{\text{hr}}\right)^2 + 4.0\left(\frac{\text{mi}}{\text{hr}}\right)^2 = 13\left(\frac{\text{mi}}{\text{hr}}\right)^2$$

$$v_R = 3.6\ \text{mi/hr}$$

$\angle BOC$ (from scale drawing) = 56°

The solution can also be found by trigonometry:

$$\tan \angle BOC = \frac{v_1}{v_2} = \frac{3.0\ \text{mi/hr}}{2.0\ \text{mi/hr}} = 1.5$$

$\angle BOC$ = 56° (No more than 2-digit accuracy is justified here)

$$\cos \angle BOC = \frac{v_2}{v_R}$$

$$0.56 = \frac{2.0\ \text{mi/hr}}{v_R}$$

$$0.56\,v_R = 2.0\ \text{mi/hr}$$

$$v_R = 3.6\ \text{mi/hr}$$

Self Check

1. What is the difference between velocity and speed?
2. If a car rounds a curve at a constant 50 mi/hr, is it traveling at uniform velocity?
3. If a car travels north at a constant 50 mi/hr, is it traveling at uniform velocity?
4. If a car increases its speed at a constant rate from 20 mi/hr to 50 mi/hr, is it traveling at uniform velocity?
5. Name two quantities, other than velocity, that are vector quantities.
6. Name two quantities that are never vector quantities.
7. You drive 600 mi in a total elapsed time (counting all stops) of 20 hr. What is your average speed?
8. How long does it take to walk 5 mi at an average speed of 4 mi/hr?
9. A train pulls out of a station at a speed of 10 mi/hr. A man in the train sprints down the aisle toward the rear of the train at 10 mi/hr. You are standing in the station watching. What is his velocity in relation to you?
10. An escalator is moving toward an upper level at 3 ft/sec. You walk up the escalator at 4 ft/sec parallel to the incline. What is your velocity with respect to the incline up which the escalator rises?

Problems

Ⓐ **1.** A car travels from Lethbridge to Edmonton in 6 hr. 20 min. Find the average speed if the distance is 316 miles.

2. When a certain driver sees an obstruction in the road, it takes him 0.80 sec to react to the obstruction and put his foot on the brake. If his car is traveling at 60 ft/sec, how many feet will it go before he puts his foot on the brake?

3. You are in a train that is traveling west at 80 mi/hr. If you walk forward in the train at 4 mi/hr, what is your velocity with respect to the earth?

4. If you walk toward the rear of the train at 4 mi/hr, what is your velocity with respect to the earth?

5. You look out of the train and see a bird flying in the same direction as the train. However, the train is going faster and the bird seems to you to be moving toward the rear of the train with a velocity of 30 mi/hr. What is the velocity of the bird with respect to the earth?

6. From your seat on the right side of the train you roll a ball at 20 mi/hr south across the floor of the train at right angles to the motion of the train. What is the velocity of the ball with respect to the earth?

Discussion Questions

1. Give examples of scalar and vector quantities other than those mentioned in this chapter.
2. How can two vectors be combined to give the largest possible resultant?
3. How can two vectors be combined to give the smallest possible resultant?
4. How could you handle a problem in which you wished to find the resultant of three vectors? For example, you are walking on the deck of a ship that is traveling in water that is moving.

Standards for Measuring Distance and Time

You have seen how motion can be described and analyzed in terms of distance and time. You have also seen how this mathematical analysis makes it possible to understand motion better, and to work with problem situations involving motion. But what of the measurements of distance and of time? Are the measuring instruments accurate? What system of units shall be used? What shall be the standards for comparison?

1–4 The mks system is used by scientists. You are accustomed to measuring length or distance in units such as inches, feet, yards, or miles, and measuring time in units of seconds, minutes, hours, days, and years. When you use a foot-rule or a tape-line, you assume that it agrees with other such length-measuring instruments. However, when you use a watch to measure time, you may question whether or not the time-measuring instrument is actually "right."

Scientists and many other people have a great need for a standardized system of measurements, so that the data of one person can be interpreted and used by another. As you might expect, it has been the scientists who have been most active and most careful in setting up standards of measurement. Indeed, the measures in common use — feet and inches, hours and minutes, pounds and ounces — have their legal status rooted in the physicists' standards of measurement.

The scientists' system of measurement is identified by the initial letters of three of its units: the meter, the kilogram, and the second. It is called the **mks system**. The meter (m) and the kilogram (kg) come from the metric system. They are the fundamental units of length and mass, respectively. The unit called the second (sec), however, comes from the time-measuring system used in ancient Babylonia at least 4,000 years ago.

1–5 The meter is the official Canadian standard of length. Although the yard as a unit of length is more familiar to most Canadians than the meter, it is the meter, not the yard, which is the official standard of length in this country. In 1959 the standards laboratories of the countries of the British Commonwealth and the United States agreed upon this definition for the yard.

$$1 \text{ international yd.} = 0.9144 \text{ m exactly}$$

Because other common units of length are multiples or fractions of a yard, this equation is the basis of definitions of these units.

$$1 \text{ mi} = 1{,}760 \text{ yd} = 1{,}609 \text{ m}$$
$$1 \text{ ft} = \tfrac{1}{3} \text{ yd} = 0.3048 \text{ m exactly}$$
$$1 \text{ in} = \tfrac{1}{36} \text{ yd} = 0.0254 \text{ m exactly}$$

At first the meter was defined as 1/10,000,000 of the distance from the North Pole to the equator at the prime meridian (zero degrees longitude). Here was a standard which could not be destroyed, barring the destruction of the earth itself. Here, scientists believed, was a standard which would never change.

A new geographic survey was undertaken to determine the exact length of the chosen distance. Then a platinum bar was made with the greatest accuracy possible at the time. Platinum was chosen because it is extremely resistant to corrosion. This bar was presented to the French government in 1799 to serve as a standard for the construction of other meter sticks. It was the standard meter for most of the nineteenth century.

Toward the end of that century, many scientists recognized the need for an international standard of length. An international bureau was established and prepared a new standard. It is made of platinum and iridium, which is less sensitive to temperature changes than platinum. The

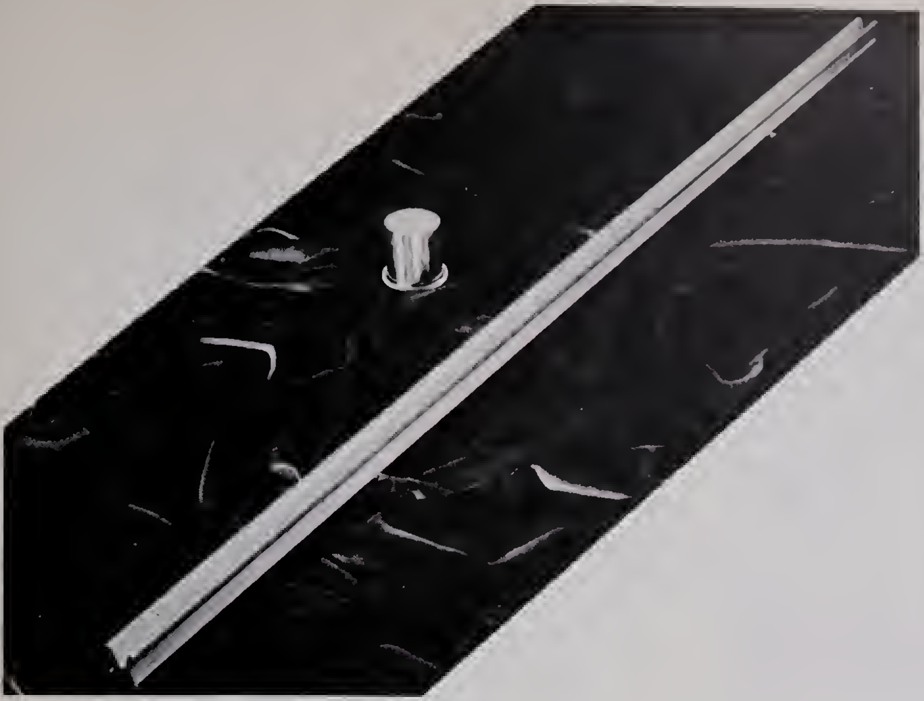


Figure 1–5a. A copy of the international prototype meter. Also shown is the international prototype kilogram.

Figure 1–5b. Today the length of the meter is based on the wavelength of light from this krypton lamp.

standard meter is called the international prototype meter and is kept on international territory in Sèvres, a suburb of Paris. Copies were distributed among the cooperating nations Fig. 1–5a.

About the time the platinum-iridium meter bars were cast, Albert Michelson, an American physicist, showed that a standard of length could be defined in terms of the unvarying wavelength of a specific color of light. In 1960 the meter was defined as 1,650,763.73 wavelengths of the orange-red light given out when the gas krypton 86 is energized under specified conditions as shown in Fig. 1–5b.

This standard meter is both permanent and practical. With it measurements can be made which are accurate to the hundred-millionth of a meter (10^{-8} m).

Table 1–1 shows the relations between various units of length in the mks system. Notice the meanings of the prefixes: *kilo-* means a thousand times; *centi-* means one one-hundredth; *milli-* means one one-thousandth.

1–6 The second is the mks standard of time. Thousands of years ago, the wise men of early Babylonia devised a way to measure the passage of a day. A pole was

Table 1–1 UNITS OF LENGTH IN THE MKS SYSTEM

Length in meters		*Name and abbreviation*
1,000.	10^{3}	kilometer (km)
1.	10^{0}	meter (m)
0.01	10^{-2}	centimeter (cm)
0.001	10^{-3}	millimeter (mm)
0.000 001	10^{-6}	micron (μ, pronounced mu)
0.000 000 001	10^{-9}	millimicron (mμ)
0.000 000 000 1	10^{-10}	angstrom (Å)

erected in the center of a circle. When the shadow of the pole was shortest — that is, at noon — a radius was drawn along the shadow line. Then, beginning at the point where the radius met the circumference, the circle was marked off into 6 equal arcs (a construction familiar to everyone who has ever handled compasses). Next each arc was bisected, and finally each of the smaller arcs was also bisected. When a number was assigned to each of the 24 arcs, it became a simple matter to describe the position of the pole's shadow at various times. Thus, it came about that the day was divided into 24 equal intervals, a division which has been used ever since.

The earth's rotation, then, provides the standard of time. A solar day is the time interval from one high noon to the next. Since there are 24 hours in a day, 60 minutes in an hour, and 60 seconds in a minute, the second was defined as 1/86,400 of a solar day.

Even so reliable a definition as this, however, presents difficulties. Not all the days of the year are the same — they vary throughout the year by as much as seven minutes. The earth is actually slowing down in its rotation — by an amazingly small but definitely measurable fraction of a second each year. Because of this, it was agreed that the second should be established not in terms of a solar day, but in terms of a solar year. So, as of now, the second is defined as 1/31,556,925.9747 of the solar year 1900.

On p. 19 you learned that the behavior of the atom is so reliable that it can be used as a standard for length. Perhaps you are wondering if this could not be true for time, also. There have been many experiments with this possibility — with a kind of device commonly called an atomic clock. This possibility has also been considered by the General Conference on Weights and Measures, the group of scientists which establishes worldwide standards for measurements. So, it may be that some future edition of this textbook will tell of the redefinition of the second — not in terms of the solar year, but in terms of the movements of subatomic particles!

1–7 Measurement systems are interchangeable. Any measurement made or expressed in one system of units can readily be converted to another system. The preferred way of carrying out such conversions is as follows:

(1) Express the relationship between the units as a ratio equal to 1. Thus, the relationship between the meter and the yard is written like this:

$$1 = \frac{3600\text{ m}}{3937\text{ yd}} = \frac{0.9144\text{ m}}{1.0000\text{ yd}}$$

(2) Think of the measurement as the product of itself and 1. For the factor 1, substitute the ratio of the units. Include the abbreviations, as well as the numerals.

(3) Carry out the multiplication, treating the abbreviations of the units as you would treat literal numbers.

See Examples 3 and 4.

EXAMPLE 3

An object moves a distance of 10,000 yd in 100.0 sec. What is its average speed in meters per second?

Given: $s = 10{,}000\text{ yd}$
$t = 100.0\text{ sec}$

To find: v_{av} in m/sec

Solution:
$$v_{av} = \frac{10{,}000\text{ yd}}{100.0\text{ sec}}$$
$$= \frac{10{,}000\text{ yd}}{100.0\text{ sec}} \times 1$$
$$= \frac{10{,}000\text{ yd}}{100.0\text{ sec}} \times \frac{0.9144\text{ m}}{1.0000\text{ yd}}$$
$$= 91.44\text{ m/sec, Answer}$$

EXAMPLE 4

The side of a square is 100.0 in in length. How is the area of the square expressed in mks units?

Given: $s = 100.0\ \text{in}$

To find: A in m^2

Solution:

$$\begin{aligned} s &= 100.0\ \text{in} \\ &= 100.0\ \text{in} \times 1 \\ &= 100.0\ \text{in} \times \frac{0.0254\ \text{m}}{1.000\ \text{in}} \\ s &= 2.54\ \text{m} \\ A &= (2.54\ \text{m})^2 \\ &= 6.452\ \text{m}^2,\ \text{Answer} \end{aligned}$$

Self Check

1. Why is the scientists' system of measurement called the mks system?
2. What is the international definition of the yard?
3. Interpret this ratio: $1 = \dfrac{25.4\ \text{mm}}{1.00\ \text{in}}$
4. Arrange in order of size, from the smallest to the largest:
   centimeter kilometer meter millimeter
5. Arrange in order of size, from the smallest to the largest:
   angstrom micron millimicron millimeter
6. What makes a wavelength of light a satisfactory basis for the definition of the meter?
7. What is a solar day?
8. Why is a solar day not a good standard of time?

Problems

Ⓐ 1. Express as a ratio equal to 1: (a) the relationship between meters and feet; (b) the relationship between meters and miles.

2. Convert these measurements to mks units: (a) 120.5 yd (to the nearest tenth of a meter); (b) 27.5 ft/sec (to the nearest hundredth of a meter per second); (c) 1,001 ft^2 (to the nearest tenth of a square meter).

3. Use the same conversion method to change 60 mi/hr to ft/sec. The conversion takes two steps. The answer is useful. Memorize it.

Accelerated Motion

1–8 Acceleration is the rate at which velocity changes with time. Suppose an automobile is moving at a speed of 40 mi/hr. Wishing to pass a car, the driver steps on the gas and, in 10 sec, increases the magnitude of the velocity to 55 mi/hr. He has accelerated the car. **Acceleration** (a), as the physicist uses the word, is the rate at which the velocity changes during a certain interval of time. Expressed in an equation:

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time interval}}$$

In the case just given, the change in velocity is 55 mi/hr − 40 mi/hr, or 15 mi/hr. The time interval is 10 sec. Therefore

$$a = \frac{15\ \text{mi/hr}}{10\ \text{sec}}$$

$$= \frac{1.5\ \text{mi/hr}}{\text{sec}}$$

Thus acceleration = 1.5 mi/hr *per sec.*

If you wish to express the answer in feet and seconds, without miles being involved, you can go back to the first line of the solution and convert 15 mi/hr to ft/sec, using the relationship found in Problem 3, p. 9.

$$60 \text{ mi/hr} = 88 \text{ ft/sec}$$

Therefore 15 mi/hr = 22 ft/sec and

$$a = \frac{15 \text{ mi/hr}}{10 \text{ sec}} = \frac{22 \text{ ft/sec}}{10 \text{ sec}} = \frac{2.2 \text{ ft/sec}}{\text{sec}}$$

Thus, acceleration = 2.2 ft/sec *per sec*. During each second, the car increases its velocity by 2.2 ft/sec.

By treating the units as algebraic symbols, physicists have developed a shorter way of writing "ft/sec per sec":

$$\text{ft/sec} \div \text{sec} = \frac{\text{ft}}{\text{sec}} \times \frac{1}{\text{sec}}$$

$$= \frac{\text{ft} \times 1}{\text{sec} \times \text{sec}} = \frac{\text{ft}}{\text{sec}^2}$$

This expression is sometimes read "feet per second squared," but it always means "feet per second per second."

The value 2.2 ft/sec^2 and the equivalent value 1.5 mi/hr per sec are *average* accelerations. The car may very well have accelerated unevenly. In solving problems in this book, you will assume that the acceleration is uniform or constant.

In equation form, the average acceleration is:

$$a = \frac{v_2 - v_1}{t_2 - t_1}$$

where v_1 and v_2 are the initial and final velocities; and t_1 and t_2 are the initial and final times. If t_1 is 0, the equation becomes:

$$a = \frac{v_2 - v_1}{t}$$

Scientists often abbreviate the equation:

$$a = \frac{\Delta v}{\Delta t}$$

1–9 Acceleration is a vector quantity.

Acceleration has direction as well as magnitude. When a car speeds up while traveling in a straight line, the direction of the acceleration is the same as that of the displacement of the car. When a car slows down, the direction of the acceleration is opposite to that of the displacement. Acceleration in the same direction as the displacement is called positive acceleration. Acceleration in a direction opposite to the displacement is called negative acceleration and is indicated by a minus sign as shown in Example 5 below.

EXAMPLE 5

A car traveling at 60 mi/hr slows down to 30 mi/hr in 15 sec. Find the acceleration in ft/sec^2.

Given:
$v_1 = 60 \text{ mi/hr} = 88 \text{ ft/sec}$
$v_2 = 30 \text{ mi/hr} = 44 \text{ ft/sec}$
$t = 15 \text{ sec}$

To find: a

$$a = \frac{v_2 - v_1}{t}$$

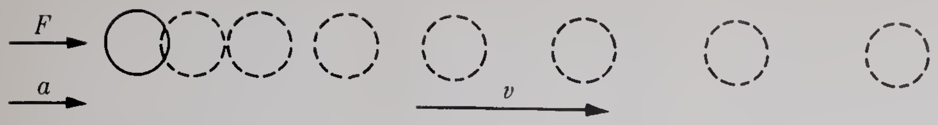
$$= \frac{44 \text{ ft/sec} - 88 \text{ ft/sec}}{15 \text{ sec}}$$

$$= \frac{-44 \text{ ft/sec}}{15 \text{ sec}}$$

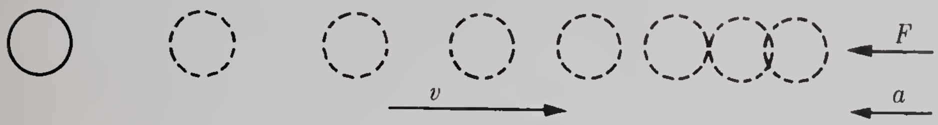
$$= -2.9 \text{ ft/sec}^2, \text{ Answer}$$

What causes an object to accelerate? If you wish to increase the speed of a ball rolling along the floor, you give it a push in the direction in which it is moving. This push, or force, gives the ball a positive acceleration (Fig. 1–6a). If you wish to slow the ball, you push against its motion, giving it a negative acceleration (Fig. 1–6b).

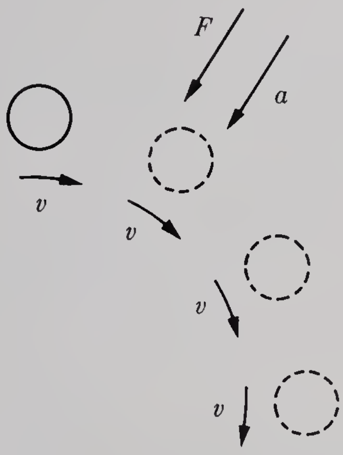
Notice that in each case the force and the acceleration are in the same direction.



a. The ball has been pushed by F in the direction shown. It goes faster. The velocity, force, and acceleration are all in the same direction.



b. A force directed against the motion of the ball is slowing it. The acceleration is in the direction of the force and opposite to the direction of the velocity.



c. To turn the ball, there must be a force at right angles to the motion. The acceleration is in the direction of the force and therefore is perpendicular to the velocity.

Figure 1–6 The relation of acceleration to force and velocity.

The change in velocity that results is a change in magnitude only, that is, a change in speed. But change in velocity is not necessarily change in magnitude. It may be change in direction only, as in turning a car without slowing down. If you change the direction of a rolling ball without changing its speed, you must give it a push at right angles to the motion, as shown in Fig. 1–6c. Here again, the acceleration is in the direction of the force and, as you can see, it is perpendicular to the velocity.

When an automobile makes a turn, it moves in a curved path. The acceleration of the car can be found if the radius of the curve and the magnitude of the velocity are known. Physicists have derived the following equation, which is very important in analyzing circular motion.

$$a = \frac{v^2}{r}$$

In this equation, a is the magnitude of the acceleration and r is the radius of the circle. The direction of the acceleration is perpendicular to the direction of the velocity.

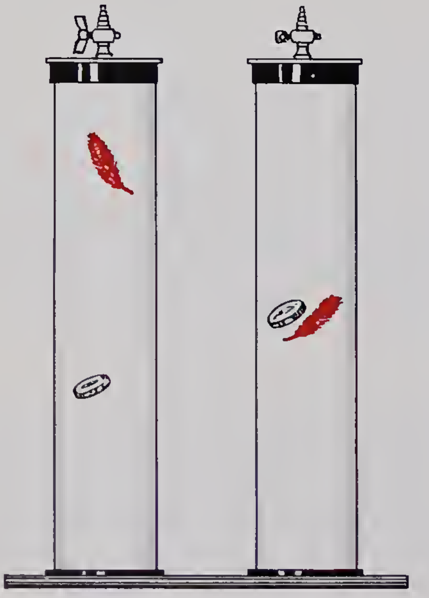
1–10 Falling objects are uniformly accelerated.

Which will fall faster, a light object or a heavy one? If you stand on a chair and drop a sheet of paper and a metal ball at the same time, the ball falls rapidly to the floor, while the paper flutters down more slowly. However, if you now crumple up the paper into as tight a wad as possible, you will find on repeating the experiment that the paper and the ball reach the floor at almost the same time.

The only difference in these two cases is that the paper when wadded into a ball presents a smaller surface for air resistance. What, then, would happen if there were no air to slow the falling paper? Figure 1–7 shows some apparatus designed to test this. The conclusion is that when the air resistance is negligible, all bodies fall at the same rate.

This conclusion, which seems contrary to everyday experience, was reached by Galileo, although he was unable to create a vacuum for testing it (see p. 25). What Galileo found, using heavy objects like gold, lead, and copper, was that it did not make any difference that one object weighed 2 lb and another weighed 20 lb. If they started out at the same time, they hit the ground together. The air resistance for short drops and dense objects of metal or stone is not great enough to be important. In fact, a study of falling bombs has shown that they must drop nearly 600 ft before air resistance begins to influence them significantly.

Figure 1–7 Each tube contains a coin and a feather. The left tube contains air. The right tube has had most of the air pumped out. Each tube is suddenly inverted so that the coin and feather start to fall at the same time. This is evidence that, in the absence of air resistance, light and heavy objects fall at the same rate.



This does not mean that bodies fall with uniform velocity. They speed up as they go. Careful measurements have shown that they are accelerated at a constant rate. The **acceleration of gravity**, as it is called, is approximately 32 ft/sec² or 9.8 m/sec². It varies slightly over the surface of the earth, being greatest at the poles. This acceleration has the special symbol *g*. When a test pilot is said to have experienced 5 *g*'s, what is meant is that he was accelerating at five times the acceleration of gravity, or 160 ft/sec².

The acceleration of gravity, like all accelerations, is a vector quantity. Its direction is toward the center of the earth. Since it is customary to think of upward vectors as being positive and downward ones as being negative, the acceleration of gravity in this book is given a negative sign:

$$g = -32 \text{ ft/sec}^2 \text{ or } = -9.8 \text{ m/sec}^2.$$

1–11 Final velocity and distance are simply calculated.

A rocket used to launch a satellite accelerates at 60 m/sec². It starts from rest ($v_1 = 0$) and burns out 180 sec after it has started.

Assuming the acceleration is uniform, the final velocity (v_2) of the rocket can be found from the equation at the top of the next page.

$$a = \frac{v_2 - v_1}{t}$$

$$60 \text{ m/sec}^2 = \frac{v_2 - 0}{180 \text{ sec}}$$

$$180 \text{ sec} \times \frac{60 \text{ m}}{\text{sec}^2} = v_2$$

$$v_2 = 10{,}800 \text{ m/sec}$$

The average velocity of the rocket is half the sum of the initial and final velocities:

$$\begin{aligned} v_{av} &= \frac{v_1 + v_2}{2} \\ &= \frac{0 + 10{,}800 \text{ m/sec}}{2} \\ &= 5{,}400 \text{ m/sec} \end{aligned}$$

The displacement of the rocket can be found by using the equation:

$$v_{av} = \frac{s}{t}$$

which can be rewritten as:

$$s = v_{av}t$$

$$\begin{aligned} s &= \frac{5{,}400 \text{ m}}{\text{sec}} \times 180 \text{ sec} \\ &= 972{,}000 \text{ m} \end{aligned}$$

1–12 A single equation will determine displacement. The displacement and average velocity equations can be combined to give a single equation for displacement s.

$$s = v_{av}t$$

$$v_{av} = \tfrac{1}{2}(v_1 + v_2)$$

Therefore:

$$s = \tfrac{1}{2}(v_1 + v_2)t$$

The equation for acceleration is:

$$a = \frac{v_2 - v_1}{t}$$

This can be solved for v_2:

$$v_2 = v_1 + at$$

Substitute this value of v_2 in the equation for s:

$$\begin{aligned} s &= \tfrac{1}{2}(v_1 + v_1 + at)t \\ &= \tfrac{1}{2}(2v_1 + at)t \\ &= v_1t + \tfrac{1}{2}at^2 \end{aligned}$$

See Example 6 below and Example 7 on the next page for problems in which these equations are used.

EXAMPLE 6

A ball is dropped from a window 64 ft above the ground. How long will it take to drop and how fast will it be going when it lands?

Given: $v_1 = 0$

$a = g = -32 \text{ ft/sec}^2$

$s = -64$ ft (measured down from window toward the ground)

To find: t and v_2

Solution: $s = v_1t + \tfrac{1}{2}at^2$

$$\begin{aligned} -64 \text{ ft} &= 0 + \frac{1}{2} \times \frac{-32 \text{ ft}}{\text{sec}^2} \times t^2 \\ &= \frac{-16 \text{ ft}}{\text{sec}^2} \times t^2 \\ t^2 &= \frac{-64 \text{ ft} \times \text{sec}^2}{-16 \text{ ft}} \\ &= 4.0 \text{ sec}^2 \\ t &= 2.0 \text{ sec, Answer} \end{aligned}$$

$$\begin{aligned} v_2 &= v_1 + at \\ v_2 &= 0 + \frac{-32 \text{ ft}}{\text{sec}^2} \times 2.0 \text{ sec} \\ &= -64 \text{ ft/sec, Answer} \end{aligned}$$

Note that the minus sign in the answer indicates downward velocity.

EXAMPLE 7

A stone is thrown vertically downward from a high cliff with an initial velocity of 10 ft/sec. How fast will it be going at the end of 5.0 sec and how far will it go between the 5th and 6th sec?

Given: $v_1 = -10$ ft/sec
$a = g = -32$ ft/sec^2
$t = 5.0$ sec and 6.0 sec

To find: v_2 at 5.0 sec
s between $t = 5.0$ sec and $t = 6.0$ sec

Solution: $v_2 = v_1 + at$

$$v_2 = \frac{-10\text{ ft}}{\text{sec}} + \frac{-32\text{ ft}}{\text{sec}^2} \times 5.0\text{ sec}$$
$$= \frac{-10\text{ ft}}{\text{sec}} + \frac{-160\text{ ft}}{\text{sec}}$$
$$= -170\text{ ft/sec, Answer}$$

$$s = v_1t + \tfrac{1}{2}at^2$$

When $t = 5.0$ sec:

$$s_5 = \frac{-10\text{ ft}}{\text{sec}} \times 5.0\text{ sec} + \frac{1}{2}\left(\frac{-32\text{ ft}}{\text{sec}^2}\right) \times 25\text{ sec}^2$$
$$= -50\text{ ft} + (-400\text{ ft})$$
$$= -450\text{ ft}$$

When $t = 6.0$ sec:

$$s_6 = \frac{-10\text{ ft}}{\text{sec}} \times 6.0\text{ sec} + \frac{1}{2}\left(\frac{-32\text{ ft}}{\text{sec}^2}\right) \times 36\text{ sec}^2$$
$$= -60\text{ ft} + (-576\text{ ft})$$
$$= -636\text{ ft}$$

$$s_6 - s_5 = -636\text{ ft} - (-450\text{ ft})$$
$$= -186\text{ ft}$$
$$= -190\text{ ft (rounded to 2 digits), Answer}$$

1–13 The velocity and acceleration of projectiles can be readily found. When an object is thrown upward, the initial velocity is positive while the acceleration of gravity is negative. All upward vectors are labeled positive and downward ones negative. For example, suppose that a ball is tossed into the air with an initial upward velocity of 64 ft/sec. How high is it at the end of 1.0 sec? In this case, v_1 is 64 ft/sec, while a is -32 ft/sec^2.

$$s = v_1t + \tfrac{1}{2}at^2$$
$$= \frac{64\text{ ft}}{\text{sec}} \times 1.0\text{ sec} + \frac{1}{2}\left(\frac{-32\text{ ft}}{\text{sec}^2}\right) \times 1.0\text{ sec}^2$$
$$= 64\text{ ft} - 16\text{ ft}$$
$$= 48\text{ ft}$$

To find the velocity at the end of 1.0 sec:

$$v_2 = v_1 + at$$
$$= \frac{64\text{ ft}}{\text{sec}} + \left(\frac{-32\text{ ft}}{\text{sec}^2}\right) \times 1.0\text{ sec}$$
$$= \frac{64\text{ ft}}{\text{sec}} - \frac{32\text{ ft}}{\text{sec}}$$
$$= 32\text{ ft/sec}$$

If you repeat this calculation for each whole value of t, you get the following results:

t (sec)	s (ft)	v (ft/sec)
0	0	64
1.0	48	32
2.0	64	0
3.0	48	−32
4.0	0	−64
5.0	−80	−96

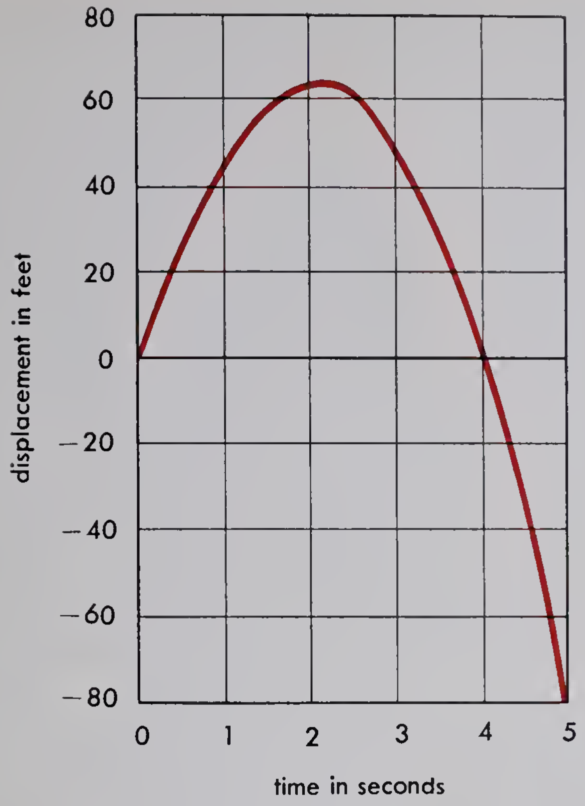


Figure 1–8 This graph shows the variation in displacement from the point of origin as the time changes when a ball is thrown upwards with an initial velocity of 64 ft/sec.

Figure 1–8 is a graph showing the changes in s as t increases. This clarifies the meaning of s in the equation. It is not the total distance traveled by the ball, but its displacement from the point of origin. At the end of 2.0 sec, the ball has reached its highest point, 64 ft in the air. The velocity has been decreasing and the table shows that now it is zero. At 3.0 sec the ball has fallen to the level it had at 1.0 sec and its velocity is now −32 ft/sec, a downward velocity equal in magnitude to the upward one at 1.0 sec. At the end of 4.0 sec, the ball is back at its starting point, coming down at 64 ft/sec, a velocity equal in magnitude to its initial upward velocity. If there were a convenient hole in the ground at this point, the ball could fall into it and at the end of 5.0 sec would be 80 ft down in the hole, traveling at 96 ft/sec. Notice the symmetry of this situation. It takes the same time for the ball to come down as for it to go up, and at any point in its path the upward velocity is equal in magnitude to the downward velocity as it passes the same point. Study Example 8 below.

EXAMPLE 8

A ball is thrown vertically upward with a velocity of 49 m/sec. How high will it rise and how long will it be in the air?

Given: $v_1 = 49\text{ m/sec}$ (upward)
$a = g = -9.8\text{ m/sec}^2$ (downward)

To find: Maximum s
Time to go up and back

Analysis: When s is a maximum, $v_2 = 0$. Therefore $v_2 = v_1 + at$ should give the time to get to the maximum height. Twice this time is the time up and back. $s = v_1t + \frac{1}{2}at^2$ will give the height.

Solution:

$$v_2 = v_1 + at$$

$$0 = \frac{49\text{ m}}{\text{sec}} + \left(-\frac{9.8\text{ m}}{\text{sec}^2}\right)t$$

$$\frac{9.8\text{ m}}{\text{sec}^2}\,t = \frac{49\text{ m}}{\text{sec}}$$

$$t = \frac{49\text{ m}}{\text{sec}} \times \frac{\text{sec}^2}{9.8\text{ m}}$$

$= 5.0$ sec to go up

Therefore: $2t = 10.0$ sec to go up and back down, Answer

$$s = v_1t + \tfrac{1}{2}at^2$$

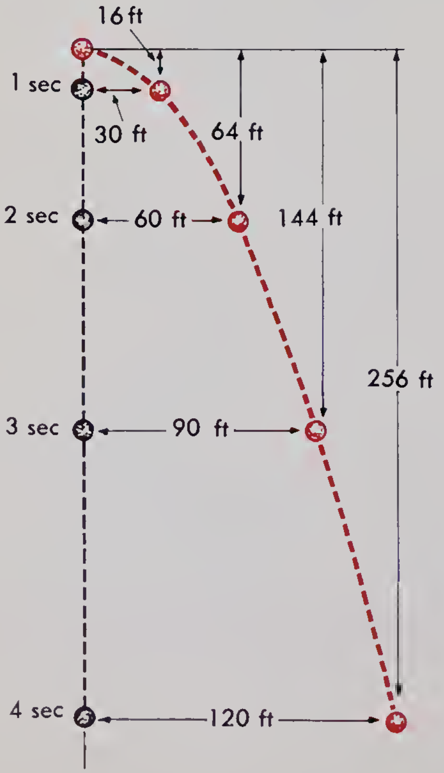
$$= \frac{49\text{ m}}{\text{sec}} \times 5.0\text{ sec} + \frac{1}{2}\left(-\frac{9.8\text{ m}}{\text{sec}^2}\right) \times 25\text{ sec}^2$$

$$= 245\text{ m} - 122\text{ m}$$

$= 123\text{ m} = 120\text{ m}$ (rounded to 2 digits), Answer

1–14 Projectiles have parabolic paths. If a ball is thrown at 30 ft/sec horizontally from a high building, it follows a curved path, as shown in Fig. 1–9. This curve is the result of two independent motions, a horizontal motion at a steady velocity of 30 ft/sec, and a vertical motion that starts with a velocity of zero and accelerates at the same rate as a ball dropped from the same point at the same time. The independence of these two motions is shown in Fig. 1–10, an actual photograph of a dropped and a projected ball.

Figure 1–9 The ball at the left is dropped at the same instant that the ball at the right is thrown with a horizontal velocity of 30 ft/sec. At the end of 1 sec, both balls have dropped 16 ft, but the one at the right has traveled 30 ft to the right. At the end of 2 sec, both have dropped 64 ft, and the one at the right is 60 ft out. At 3 and 4 sec, both balls have dropped equal distances, and the ball that was thrown has traveled a horizontal distance of 30 ft/sec × the time. A ball that has a horizontal velocity keeps a steady horizontal rate that is independent of its vertical motion. The trajectory, or shape of its path, is a parabola.



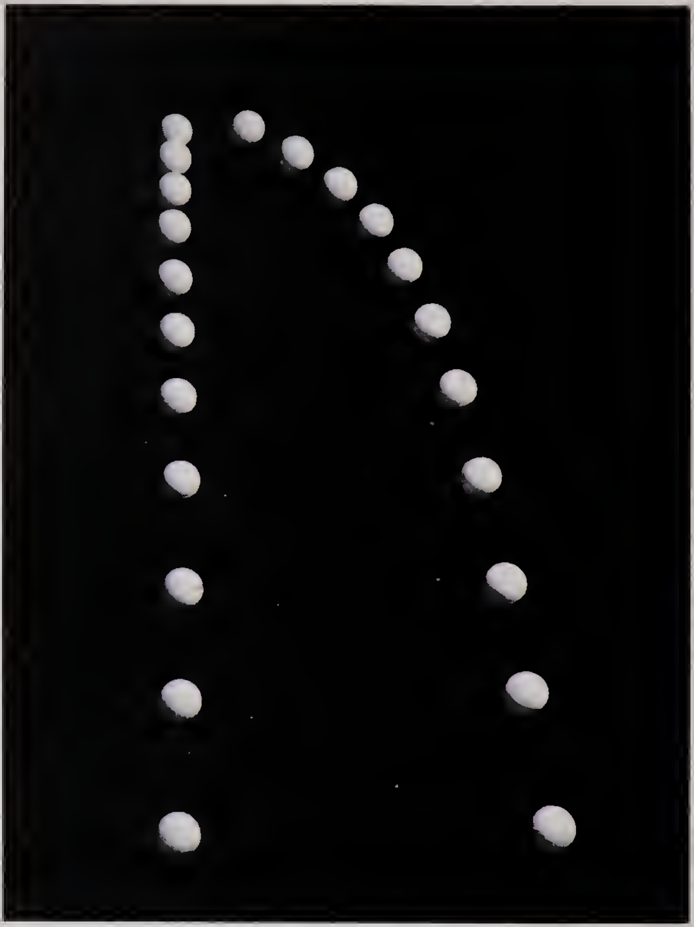


Figure 1–10 This stroboscopic photo shows that a ball which is projected horizontally falls at the same rate as a ball which is dropped.

The independent horizontal and vertical motions combine to produce a curved path, which is called the **trajectory of the projectile**. The shape of the curve is a **parabola** See Fig. 1–11 on p. 17.

To solve a problem about a projectile, separate the horizontal and the vertical parts of the problem and then calculate them individually, as shown in Example 9.

At high speeds, air resistance influences the motion of a projectile measurably. However, as noted on p. 12, air resistance is negligible for a heavy object falling 600 ft or less. Problems 4, 5, and 6 on p. 30 and Discussion Question 6 on p. 25 illustrate the effect of air resistance on a longer fall. In solving other problems, assume that air resistance is negligible.

EXAMPLE 9

A gun held horizontally is fired at a target 1000 ft away. If the bullet has a muzzle velocity of 2500 ft/sec, how far will the bullet drop as it travels to the target?

Given:

Horizontal problem	Vertical problem
$s = 1000$ ft	$a = g$
$v = 2500$ ft/sec	$= -32$ ft/sec^2
	$v_1 = 0$

To find: s (for vertical problem)

Analysis: The purpose is to find s in the vertical problem. If you knew t, you could solve the problem by using $s = v_1t + \frac{1}{2}at^2$. You can use the horizontal problem to find t. Here there is no acceleration, so $v = s/t$. From this you can find t.

Solution: Horizontal problem:

$$v = \frac{s}{t}$$

$$vt = s$$

$$t = \frac{s}{v} = \frac{1000\text{ ft}}{2500\,\frac{\text{ft}}{\text{sec}}} = \frac{1000\text{ ft}}{2500} \times \frac{\text{sec}}{\text{ft}}$$

$$= 0.40\text{ sec}$$

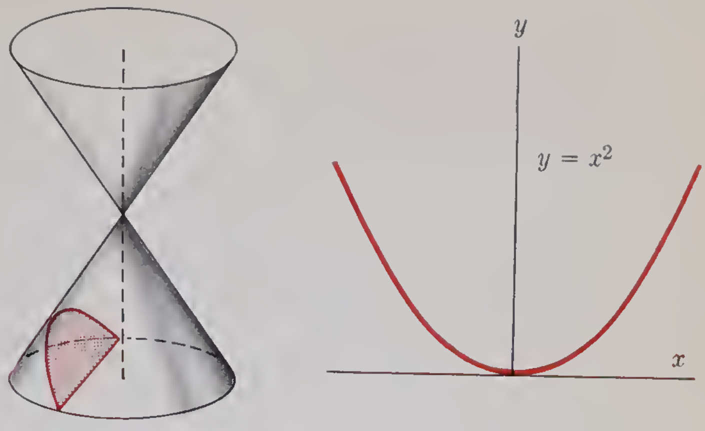
Vertical problem:

$$s = v_1t + \tfrac{1}{2}at^2$$

$$= 0 + \frac{1}{2} \times \frac{-32\text{ ft}}{\text{sec}^2} \times (0.40\text{ sec})^2$$

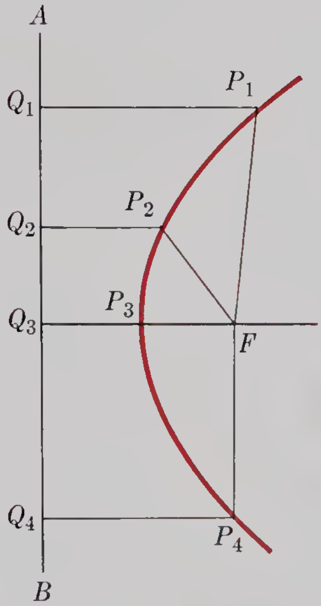
$$= \frac{-32\text{ ft} \times 0.16\text{ sec}^2}{2 \times \text{sec}^2}$$

$$= -2.6\text{ ft, Answer}$$

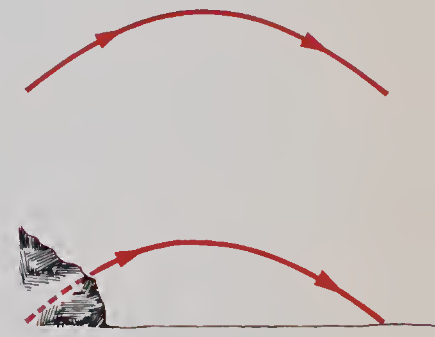


A parabola is the curve obtained when a cone is sliced parallel to one of its sides.

The graph of $y = x^2$ is a parabola.



A curve drawn so that every point P on it is equally distant from a focus F, and a line AB is a parabola. Here every PF value equals the corresponding PQ value.



The path of a projectile is a part of a parabola. Whenever a body is moving so that it is uniformly accelerated in one direction (downward here) and moves with uniform velocity in a direction perpendicular to the accelerated one (horizontal here) its path will be a parabola.

Figure 1–11 What is a parabola?

Summary of formulas relating to uniformly accelerated motion

$$a = \frac{v_2 - v_1}{t},$$

which is the same as

$$v_2 = v_1 + at$$

$$s = v_{av}t$$

$$v_{av} = \frac{v_2 + v_1}{2}$$

$$s = v_1t + \tfrac{1}{2}at^2$$

Self Check

1. An object traveling west at 10 ft/sec speeds up without changing direction to 20 ft/sec in 2.0 sec. What is the acceleration?
2. An object traveling west at 20 ft/sec slows down to 10 ft/sec in 2.0 seconds without changing direction. What is the acceleration?
3. An object traveling at 10 ft/sec moves along a curved path without changing speed. In what direction is the acceleration?
4. What is the acceleration of gravity in metric and English units?
5. If you dropped a sheet of newspaper and a copper pellet having the same weight as the newspaper from a window at the same time, which would you expect to reach the ground first? Why?
6. Who made the first scientific study of the behavior of falling objects?
7. What conclusion did he reach that could not be accurately checked until modern times?
8. A ball is dropped from a high cliff. How far does it fall in 2.0 sec?
9. A bullet is fired directly up with a speed of 500 m/sec. What value of g would you use in solving a problem about the bullet?
10. What equation would you use to find the position of the bullet at the end of 6 sec?
11. What is the shape of the path of a projectile?

Problems

A **1.** A car starts from rest and accelerates in a straight line to 60 mi/hr in exactly one minute. What is its acceleration in mi/hr per sec and in ft/sec^2?

2. A boy on a bicycle travels in a straight line and slows down from 30 ft/sec to 10 ft/sec in 5.0 sec. What is his acceleration?

3. A plane traveling at 200 mi/hr accelerates at the rate of 5.0 mi/hr per sec. for 1.0 min. What is its final speed?

4. An officer of the U.S. Aerospace Medical Laboratory jumped from a ballon 76,400 ft. high and fell without a parachute for 2 min. 58 sec. He was travelling at 140 mi/hr at the time that his parachute opened. What was his average acceleration in mi/hr per sec and in ft/sec^2? Why is this value not equal to g?

5. If he had been falling in a vacuum for the same length of time, how far would he have fallen?

6. In a vacuum, how long would it have taken the man in Problem 4 to reach his final speed of 140 mi/hr?

7. A stone thrown horizontally from the top of a skyscraper takes 8.64 sec to reach the street. How high is the building?

8. A stone is dropped from the edge of a cliff and hits the ground in 5.0 sec. How high is the cliff and what is the velocity of the stone when it hits the ground? Use metric units.

9. What is the distance traveled by the stone of Problem 8 between the 3rd and 4th sec?

10. What is the average velocity of the stone of Problem 8 between the 3rd and 4th sec?

11. A ball is thrown vertically up from a window at 10 m/sec and hits the ground in 5.0 sec. What is the height of the window?

12. A ball is thrown vertically down from a window at 10 m/sec and hits the ground in 5.0 sec. What is the height of the window?

13. A ball is thrown horizontally from a window at 10 m/sec and hits the ground in 5.0 sec. What is the height of the window and how far from the base of the building does the ball hit?

B **14.** What is the acceleration of a car traveling at 30 mi/hr in a curve with a radius of 100 ft?

15. Derive an equation for the velocity of an accelerated object when you know the initial velocity, the acceleration, and the distance it is from the starting point.

Measurement

1–15 A scientific measurement consists of a number and a unit. Understanding natural things involves describing them. The more accurate the description, the better the understanding. An accurate description answers such questions as: How long? How fast? How loud? In other words, it is *quantitative*. Therefore it must make use of mathematics.

One part of every measurement made in physics consists of a number. The other part is the name of the unit of measurement, usually abbreviated. Thus, the edge of this page is 0.23 m in length; that is, twenty-three hundredths of 1 meter. The measurement is not complete unless both the numerals and the units are included.

1–16 Scientific notation uses exponents. In physics you frequently work with numbers which are very large or very small. It is convenient to express such numbers in powers of ten. This is known as **scientific notation**. For example, a value such as the speed of light, 300,000,000 m/sec, can be easily expressed as 3×10^8 m/sec. An angstrom unit, which is 0.000 000 000 1 m, can be expressed as 10^{-10} m.

A number between 1 and 10 is not necessarily an integer: 2.9 is just as truly between 1 and 10 as 3 is. Therefore to express the more accurate value of the speed of light, 299,800,000 meters per second, the number 2.998 is used as one factor.

$$299{,}800{,}000 \text{ m/sec} = 2.998 \times 100{,}000{,}000 \text{ m/sec}$$

$$\text{speed of light} = 2.998 \times 10^8 \text{ m/sec}$$

1–17 Every measurement is an approximation. To say that a dollar bill is 6.9 cm in width means that the measurement was closer to 6.9 cm than it was to 6.8 cm or to 7.0 cm. Actually, this measurement could be made with a scale whose closest markings were centimeter marks — a scale with no divisions between those for centimeters. The reason that this is possible is that it is completely practical to estimate to the nearest tenth of the smallest division of the scale you are using. Perhaps you cannot do this very precisely now, but with a little practice you will be able to do it very well. When a measuring instrument is marked in tenths of a centimeter (as most centimeter scales are), a length measured with it should be read and recorded to the nearest hundredth of a centimeter.

Suppose the width of a dollar bill seems to come exactly at the 6.9 cm mark on such a scale. Then you would report the measurement as 6.90 cm. To do so is to state that you have used a scale marked in tenths of a centimeter, and that you believe the measure of the edge to be closer to 6.90 cm than to 6.89 cm or to 6.91 cm.

1–18 Percent of error can be determined. No matter how close the markings on a scale may be to each other, there is a limit of preciseness beyond which you cannot go. Every measurement on any scale leaves something to be desired. These discrepancies are not mistakes — they are errors. They cannot be avoided.

The size of the unavoidable possible error of measurement depends on the scale of the measuring instrument used. This error can be expressed as a percent.

An error of 0.05 cm in a measurement of 6.9 cm is not very large – less than 1 percent. An error of 0.05 cm is a measurement of 15.3 cm (the length of a dollar bill) is even smaller.

$$\frac{0.05 \text{ cm}}{6.9 \text{ cm}} = 0.7\% \qquad \frac{0.05 \text{ cm}}{15.3 \text{ cm}} = 0.3\%$$

1–19 Measurement errors must be minimized. Although there is always an error of measurement which cannot be avoided, there are also sources of error which can be reduced or eliminated. One source of error in every measurement is the instrument used.

For example, some centimeter scales are more accurately made than others. A steel or ivory scale, with divisions marked by fine scratches, is a better instrument than a wood or celluloid scale with divisions marked by ink or paint.

Even the best of instruments may become worn with use. Even the best of instruments is affected by conditions which are hard to control, such as temperature changes.

To reduce the size of errors due to measuring instruments, physicists repeat their observations whenever possible. It is common to make several measurements of a single length, starting at a different point on the scale each time. The average of these measurements — the mean value — is a more reliable figure for the true value than any one observation.

Another reason for taking several measurements is that the length being measured might be different when measured in different directions. For example, a broomstick might have various diameters depending on the direction in which it is measured.

Physicists have another reason for repeating their observations: to identify their own errors. Everyone makes occasional mistakes in measuring. Accordingly, no one should assume that his measurements are always correct. If one measurement is far different from the others, it is not used in finding the average. It is not erased from the record, but a note is made that the figure has been rejected.

1–20 Significant digits express the degree of accuracy of measurements. A measurement of 6.9 cm is said to be expressed with two-digit accuracy. There are two digits in the number. The first digit is certainly correct and the latter is based on a reasonably sure estimate. The values of 6.87 cm and 15.3 cm are expressed with three-digit accuracy, while the value of 15.30 cm is expressed with four-digit accuracy.

The decimal points in these values have nothing to do with the accuracy. The accuracy is conveyed by the **significant digits** which are the results of measurement, with the last digit estimated. There are three significant digits in both 15.3 cm and 153 mm, and there are four significant digits in both 15.30 cm and 153.0 mm. Notice that these zeros are significant.

When you make measurements, record all the significant digits, including the significant zeros. Sometimes you will also have to include zeros which are not significant. For instance, to report a measurement of 6.9 cm in meters, you would write 0.069 m. Here the zeros are not significant. They serve merely to locate the decimal point.

Some numbers are exactly correct. For example, if there are 38 students in your class, this is an exact number. The number of significant digits in this number is infinite, for it would be correct to write it 38.000, with 0's going on forever. Another kind of exact number is one that is set by a definition. For example, when the international definition of the yard is given as 0.9144 m exactly, this means 0.914400 . . . . , with zeros going on forever. There are an infinite number of significant digits.

Suppose that you were to compute the area of a dollar bill from dimensions measured to the hundredths of a centimeter; that is, 15.30 cm and 6.87 cm. Because one of these measurements was made with only three-digit accuracy, there can be no more than three significant digits in the result.

$$\begin{aligned}\text{Area} &= 15.30\ \text{cm} \times 6.87\ \text{cm}\\ &= 105.1110\ \text{cm}^2\\ &= 105\ \text{cm}^2\end{aligned}$$

This rule applies when one number is multiplied or divided by another.

When you are adding or subtracting, however, you handle the significant digits not on the basis of how many there are altogether, but how many there are after the decimal point. For example, here are the weights of five pieces of metal: 4.8 g, 11.3 g, 0.15 g, 16.417 g, and 398 g. The key figure is the last item in the list — it has no significant digits beyond the decimal point. Therefore, all the figures are rounded off to the nearest *whole* number before proceeding with addition.

4.8 g		5 g
11.3		11
0.15		0
16.417		16
398.		398
	Total	430 g

Take another look at the rounded-off sum in the last paragraph. It was 430 grams, and you know that it has three significant digits because you saw how it was obtained. However, if you report a measurement as 430 grams, a reader may not know whether there are three significant digits or only two, with the 0 being there merely to indicate the decimal point. In such cases, you can show the number of significant digits clearly by using scientific notation. The sum then becomes 4.30×10^2 grams. It is customary in scientific notation to write only one digit before the decimal point.

In this book, if you see a whole number that ends in one or more 0's, you are to assume that the 0's are significant digits unless you are told otherwise. Thus 3000 m has four significant digits. If it had only two, it would be written 3.0×10^3 m.

It is usually simple to round off numbers to the nearest designated digit. However, there is a problem when a number like 4.85 is to be rounded off to the nearest tenth. It could be 4.8 or 4.9. The usual rule for rounding off a "5" is to round it off to the nearest *even* number. Thus, 4.85 would be rounded off to 4.8, and 4.55 would be rounded off to 4.6.

Self Check

1. What are the two parts of every measurement?
2. The earth's circumference is 40,000,000 m. If you assume that there are three significant figures, what is this value in scientific notation?
3. A sheet of paper is 0.000,08 m thick. What is this thickness in scientific notation?
4. The distance traveled by light in 1 yr is 5.9×10^{12} mi. This distance is called 1 light year. What is the distance in miles of a group of stars believed to be 140,000,000 light years from earth?
5. A student learning to use a vernier caliper made five measurements of the diameter of a worn five-cent piece, and recorded these values: 2.11 cm, 2.14 cm, 2.13 cm, 2.31 cm, 2.10 cm.
   (a) How many significant digits are there in the last of the recorded values?
   (b) Should any of the values be rejected? If so, which?
   (c) What value should be used to compute the area of the flat surface of the coin?
6. What is the difference in meaning between a measurement expressed as 4.6 m and one expressed as 4.60 m?

7. Which distance can be measured with less error using a high quality meter stick, one of about 8 cm or one of about 80 cm?
8. What are two advantages of making important measurements several separate times?

Problems

A **1.** Write in scientific notation (assume that the 0's are not significant digits) : (a) radius of the sun = 700,000,000 m; (b) thickness of an oil film = 0.000,000,005 m.

2. A student measures the acceleration of gravity and reports that it is 9.75 m/sec^2. What is his percent of error, assuming that 9.80 m/sec^2 is the accurate value? Report one significant digit.

3. A rectangle is measured and found to be 24 cm long and 21 cm wide. What is its area? Show significant digits clearly.

4. What is the sum of the following: 6.798 m; 0.29 m; 1.008 m; 0.03 m?

B **5.** The nautical mile is 6,076.103 ft, correct to the nearest thousandth of a foot. Using the international yard (0.9144 m) as an exact figure, determine the number of kilometers in a nautical mile correct to three significant digits. To how many significant digits could your answer be carried?

6. The equatorial radius of the earth is 6.378×10^6 m. What is the length of the equator? Use a value of pi that will give you the maximum number of significant digits.

Discussion Questions

1. What are two advantages of expressing certain numbers in terms of powers of ten?
2. How would you answer a person who argues that exponents are silly – after all, raising a number to the two-thirds power is as ridiculous as shooting a gun two thirds of a time?
3. It has been stated that every measurement is, in the final analysis, an approximation. Is this true when the butcher determines the number of pounds of meat on the scale? Is it true when the grocer determines the number of eggs in a carton? Why?
4. What is the difference between errors and mistakes in making measurements? How can errors be minimized? How can mistakes be minimized?
5. A workman uses a highly precise micrometer to measure the diameter of a piece of wire. For six measurements he gets these figures: 1.52 mm, 1.50 mm, 1.49 mm, 1.30 mm, 1.51 mm, 1.53 mm. What do you conclude about the accuracy of the measurements? about the shape of the wire?
6. How can you explain the fact that multiple measurements of a given dimension can provide a mean value which is more reliable than any single one of the individual measurements?

Chapter Summary

Speed is the rate of change of distance per unit time. Velocity is speed in a specified direction. Uniform velocity is velocity which does not change in magnitude or in direction. Even though velocity may not be uniform, it is possible to compute average velocity during a specified interval. Vector quantities have both magnitude and direction, while scalar quantities have magnitude only. Velocity is a vector quantity; speed is a scalar quantity. Vector quantities are added by special methods.

Scientists use the mks system of measurements. In this system, the meter is the standard unit of length, the kilogram is the standard unit of mass, and the second is the standard unit of time. At present, the meter is defined in terms of the wavelength of the orange-red light given off by krypton 86. The meter is related decimally to larger and smaller units of length; the second is related decimally to smaller units of time.

Acceleration is the rate at which velocity changes with time. It may involve either a change in magnitude or a change in direction or both. Acceleration is a vector quantity. Falling bodies are uniformly accelerated. The acceleration of gravity (g) is constant in any given location. Horizontal and vertical movements of a projectile are independent of each other. The trajectory of a projectile is a parabola.

A measurement consists of a number and a unit of measurement. Physics involves much mathematics. Exponential notation is commonly used in physics calculations, particularly for very large and very small numbers. Quantities expressed in exponential notation can be multiplied or divided by each other easily.

Measurements are always approximate, and involve unavoidable errors of measurement. Errors in measurement are commonly expressed in terms of per cent. The accuracy of a measurement or a computation based on measurement is properly expressed by the number of significant digits recorded. The result of a computation is no more accurate than the measurements it includes.

Vocabulary

You should be able to define the following words and expressions. The number refers to the page on which the word is first introduced.

- velocity (*p.* 2)
- vector quantity (*p.* 2)
- speed (*p.* 2)
- scalar quantity (*p.* 2)
- displacement (*p.* 2)
- uniform velocity (*p.* 2)
- average velocity (*p.* 2)
- delta notation (*p.* 2)
- resultant (*p.* 3)
- vector sum (*p.* 4)
- mks system (*p.* 6)
- micron (*p.* 7)
- millimicron (*p.* 7)
- angstrom (*p.* 7)
- solar day (*p.* 8)
- atomic clock (*p.* 8)
- acceleration (*p.* 9)
- acceleration of gravity (*p.* 12)
- projectile (*p.* 16)
- trajectory (*p.* 16)
- parabola (*p.* 16)
- scientific notation (*p.* 19)
- percent of error (*p.* 19)
- significant digits (*p.* 20)

Problems

A

1. The pilot of a plane heads due north at 240 mi/hr. A wind is blowing from the west at 40.0 mi/hr. What is the plane's velocity with respect to the earth?

2. How far will the pilot of Problem 1 be off course at the end of 4 hr if he hoped to travel due north and forgot to check the wind velocity?

3. Convert (a) 8.7 cm to in; (b) 21.8 ft to m.

4. A bicycle moving at 10 ft/sec speeds up at the rate of 3.0 ft/sec^2. How fast is it going at the end of 5.0 sec?

5. How far does the bicycle of Problem 4 travel in the 5.0 sec? Solve two ways and thus check your answer.

6. An automobile increases its speed from 20 mi/hr to 50 mi/hr in 15 sec. How far will it travel during the interval?

7. If a stone is thrown out horizontally at 30 ft/sec from a cliff 400 ft high, how long would it take for the stone to reach the ground, and how far away from the base of the cliff would it strike?

8. A ball is thrown vertically up and returns to the hand in 5.0 sec. What was the initial velocity and how high did it go? Give answers both in metric and English units.

9. A bomber flying at 400 mi/hr at an elevation of 10,000 ft drops a bomb. Because of the motion of the bomber, the bomb starts with a horizontal velocity of 400 mi/hr. Assuming air resistance to be negligible, how far before the plane is over the target must the bomb be released?

10. Write in scientific notation. Assume that the 0's are not significant digits: (a) Distance of sun from earth = 149,000,000,000 m; (b) Wavelength of ultraviolet light = 0.000 000 292 m.

11. The value of π has been computed out to thousands of decimal places. Carried out to ten decimal places, π is 3.1415926536. How many significant digits are there in this number? Express this number using two significant digits, eight significant digits.

B **12.** Can you devise a method for finding the total time in Example 8, rather than finding half the time and doubling it?

13. A projectile travels farthest horizontally if it is launched at an angle of 45°. If you can hurl a ball at 80 ft/sec, what is the widest river across which you can throw it?

14. A speed record for manned flight was 1,390.21 mi/hr. Express this record in meters per second, using the exact international definition of the yard.

Discussion Questions

1. Which gives the larger resultant, two vectors at an acute angle, or the same two vectors at an obtuse angle?
2. Why have official standards for length and time changed so much during the last few centuries?
3. Aristotle, the ancient Greek scholar, taught that if one object was 10 times as heavy as another, it would fall 10 times as fast as the lighter object. What ordinary observations might have led him to this conclusion?
4. How should a gun be aimed with respect to a target a considerable distance away in order to hit it?
5. In measuring distances in outer space, the "astronomical unit" is often used. This unit is based on the earth's distance from the sun. For this to be a permanent and unchanging standard, how must it be defined?
6. During a free fall from 76,400 to 12,000 ft, a man reached a maximum downward velocity of 423 mi/hr and then slowed to 140 mi/hr, before opening his parachute. How can you account for this?
7. A bombsight uses a complex computer that determines when a bomb should be released from a plane in order to hit a target. What is some of the information that must be supplied to the computer for it to make its calculations?

Work on Your Own

1. Read some of Galileo's writings about falling bodies as shown in his book *Two New Sciences* (Dover, 1953). You will also find his writings discussed and quoted in *Foundations of Modern Physical Science* by Holton and Roller (Addison-Wesley, 1958).
2. The horizontal distance traveled by a projectile with a certain muzzle velocity is greatest if the projectile starts out at an angle of 45° above the horizontal. Design an experiment to test this. If you wish, you can find the mathematical proof in many college physics books.
3. Devise a system to measure g. A college laboratory manual may give you ideas.

PHYSICS HALL OF FAME

Galileo Galilei · 1564–1642

There is a story that Galileo climbed the Leaning Tower of Pisa one day and dropped balls of different weights to demonstrate to a crowd that Aristotle was mistaken when he said that the speed of a falling object depends on its weight. Galileo probably did not perform the experiment for a crowd, for there is no record of the event. However, he did write a book in which he has an imaginary person, Salviati, tell about dropping balls from a height of 100 cubits (about 150 feet), which is approximately the height of the Tower of Pisa. Possibly Galileo, who taught at Pisa, had used the Tower privately. Salviati reports that there was very little difference in the speed of fall of the balls, and concludes that "in a medium totally devoid of resistance all bodies would fall with the same speed." This conclusion was unpopular. Most scholars believed that Aristotle could not be wrong, that even to question him was heresy.

Galileo continued to experiment. He built a telescope and discovered the moons of Jupiter and the phases of Venus. At the time nearly everyone believed that all heavenly bodies revolve around the earth. The phases of Venus, however, showed that Venus must revolve around the sun. Similarly, Galileo saw clearly that the moons of Jupiter revolve not around the earth but around Jupiter. Such observations led Galileo to state that the earth, like Venus, revolves around the sun, a theory developed earlier by the astronomer Copernicus. This was the most unpopular idea of all. Galileo was ordered to stop advocating the heliocentric theory. He wrote more about it, however, and as a result was sentenced to spend the rest of his life in retirement.

For the men who opposed Galileo, science was in the ancient books and was not to be questioned. For Galileo, science lay in experimentation and direct observation, and no authority was to be considered infallible. He broke a long tradition of blind acceptance of authority, and his work may justly be thought of as the beginning of modern science.

CHAPTER 2

Courtesy of Bell Aerosystems Company.

Wearing a rocket belt, this man leaped 15 feet high and landed about 50 feet from his starting point.

Force and Motion

The man in the picture opposite is not hanging by invisible wires from above, nor is he standing on some support hidden in the dust below his feet. He is jumping, and making a much higher and longer jump than the world's record for the broad jump. He is wearing a rocket belt that enables him to jump as much as 50 feet in one leap. Imagine being able to cross a small river at one bound, or being able to step off a 50-foot cliff and make a slow-motion landing!

Today nearly everyone knows something about rockets, so probably you have a fair idea of how the rocket belt works. A full understanding, however, involves the concept of the relation of force to motion. The purpose of this chapter is to explain to you that concept.

Force and Velocity

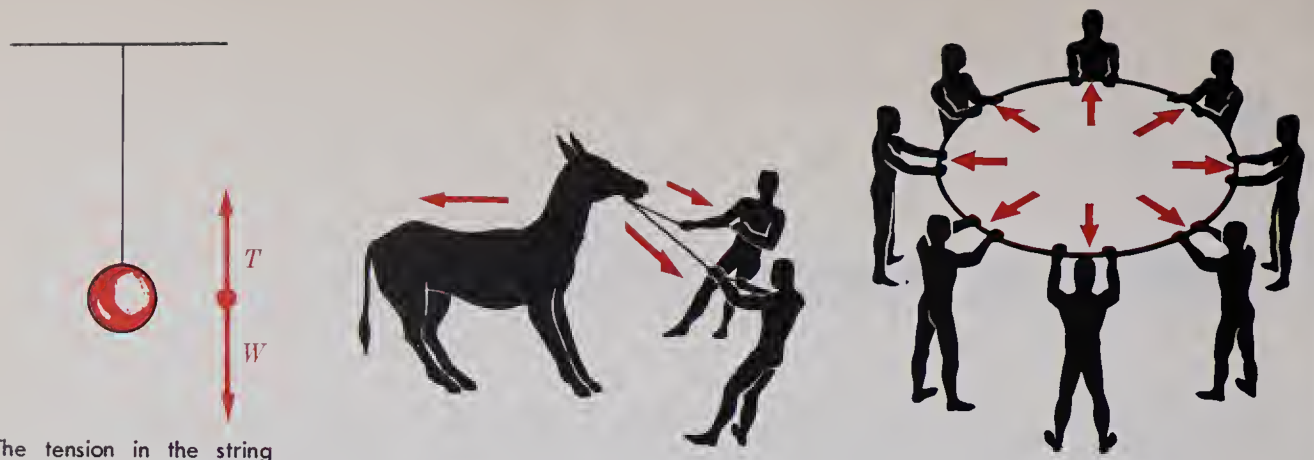
2–1 What is a force? A force is often defined as a "push" or a "pull." There is nothing untrue with this statement, but it does not really tell you much about a force. Instead of defining force, it substitutes a synonym. A physicist prefers to define a force in terms of what it does.

Just what does a force do? Suppose you squeeze a balloon, without breaking it. The obvious result is that you change its shape. Now suppose you were to hold the balloon in the palm of one hand and give it a sharp blow with the other hand. It will move off. At the moment when you struck the blow, if you could have examined the balloon carefully, you would probably have found that it was also somewhat out of shape.

A force, then, can do two things. A **force** can change the shape of an object; it can change the velocity of an object. This is called an **operational definition** of a force because it describes an activity to make clear what is meant by the word.

2–2 Forces may be balanced or unbalanced. The steel ball suspended from a wire in Fig. 2–1a has two forces acting on it, its weight, acting vertically downward, and the force exerted by the wire, acting vertically upward. Since these forces are equal in magnitude and opposite in direction, their resultant is zero.

The two men trying to start the balky mule in Fig. 2–1b are getting nowhere because the mule exerts just the right amount



a. The tension in the string pulls the ball up with a force equal to the downward pull of its weight. The resultant is zero.

b. The resultant of these three forces is also zero.

c. The resultant of the horizontal forces exerted by the firemen on the blanket is also zero.

Figure 2–1 When the resultant of a group of forces acting on the same object is zero, the forces are balanced. When the resultant is not equal to zero, the resultant is an unbalanced force.

of force to make the resultant force on his harness equal to zero.

The firemen in Fig. 2–1c pull outward on the blanket with a variety of forces in a variety of directions, but the resultant is zero. These are all examples of **balanced forces**; that is, forces whose resultant is zero. On the other hand, if two children pull on a favorite toy, and one pulls with a force of 10 pounds, while the other pulls with a force of 8 pounds in the opposite direction, there is a resultant force of 2 pounds in the direction of the stronger child. This 2-pound resultant is an unbalanced force. Whenever the resultant of a group of forces *acting on the same object* is not equal to zero, their resultant is called an **unbalanced force**

2–3 An unbalanced force changes the velocity of an object. If you push a ball on a level floor, you start it rolling. If you put out your hand in the path of the ball and apply a force opposed to its motion, you can stop the ball. If, on the other hand, you apply a force at an angle to the motion, you change the direction of the motion (Fig. 2–2a, b, and c). All of these changes are changes in velocity produced by unbalanced forces. If you push equally with both hands in opposite directions, however, the forces balance, as shown in Fig. 2–2d, and there is no change in velocity.

It is obvious that if you did not push the stationary ball, it would not move. But even if you do not put out your hand to stop the rolling ball in Fig. 2–2, it slows down and comes to rest. Does this mean that a force is not absolutely necessary in order to slow down a ball? Does it also mean that if you want the ball to keep going, you must continue to supply an unbalanced force?

These questions have puzzled people for centuries. The ancient Greeks decided that the natural state of any object was that of rest and that a force is always required to keep it moving. This is such a natural idea that it took a great genius like Galileo to start to doubt it. Sir Isaac Newton, born in 1642, the year of Galileo's death, also doubted it. He thought that people were overlooking some of the forces that were acting on the rolling ball. After you stop pushing it, it continues to roll. But the air gets in the way and must be pushed aside. There is friction between the ball and the floor. Air resistance and friction are forces that retard the motion of the ball.

When you are pushing the ball, your

push is greater than the forces of air resistance and friction; the forces are not balanced. Therefore the ball speeds up. When you stop pushing, the forces of air resistance and friction have nothing to oppose them. The resultant unbalanced force on the ball slows it down.

Newton stated his conclusions in the form of a law: A body at rest will remain at rest unless an unbalanced force acts upon it. A body in motion will remain in motion in a straight line at a steady speed unless an unbalanced force acts upon it. The law can also be stated: The velocity of a body remains constant unless acted on by an outside, unbalanced force. This is called **Newton's first law of motion.**

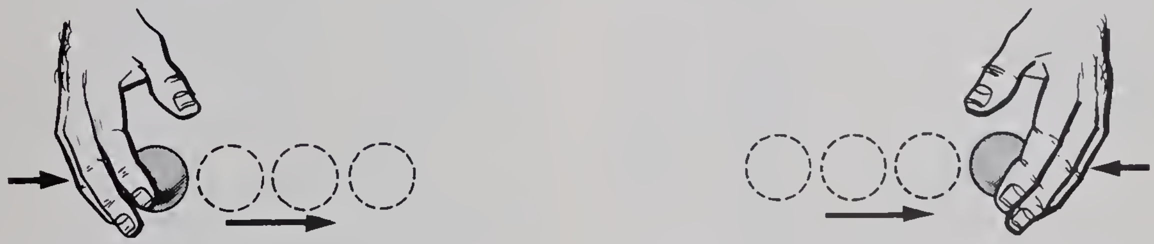
A law passed in a legislature often carries the name of the man who sponsored it and persuaded his fellow-legislators to vote for it. Newton's law is not of this sort; it is a scientific law.

A **scientific law** is a description of the way in which the universe and its parts behave. This is a law-abiding universe. The sun does not rise in the east one day and in the north another. If you let go of a ball, it drops to the floor every time. It does not fall some days, rise on others, and go off horizontally every once in a while.

One of the things scientists do is to try to formulate laws which accurately describe the behavior of the universe. Sometimes a law is incompletely stated and therefore is restated as new facts are learned.

The notion of the ancient Greeks that moving objects slow down unless they are pushed is an example of an incomplete statement of a scientific law. It certainly seemed true on the surface of the earth, but they were unaware of the forces of friction and air resistance. But out in space, where these forces do not exist, an object may travel for millions of miles without slowing

Figure 2–2 The effect of unbalanced and balanced forces on a ball.



a. If you push the ball, it starts to roll.

b. If you push against the motion of the ball, you can stop it.

c. If you push at an angle to the ball's motion, you change the direction of the motion.

d. If you apply balanced forces, you merely squeeze the ball.

Figure 2–3 A safety belt will apply a force to slow you down when a plane lands or a car stops suddenly so that you will not be as likely to get hurt by continuing in forward motion.

down; and on earth we can observe that the more that friction and air resistance are reduced, the longer an object moves without stopping. Newton's law is a better description of the behavior of the universe than were the earlier ideas.

2–4 All objects possess inertia. If you are sitting in a car at the right of the driver and he suddenly puts on the brake, your body jerks forward and you may hit your head on the windshield or the panel below it. If you think of this in terms of the forces acting, you see that you really were not jerked forward. Instead a force was applied to the car to slow it down. But no such force was applied to you. Result: you kept on going (Fig. 2–3).

What happens if you are sitting in a car when the driver suddenly speeds up? You feel as if you are being pushed back into your seat. A force has been applied to the car to accelerate it. Since the force was not applied to you, you were left behind for a moment. The seat was moving forward faster than you were and therefore pushed you from behind.

Any object, in this case your body, behaves according to Newton's first law. The tendency of an object to continue in motion if it is in motion or to stay at rest if it is at rest is called **inertia**. Inertia may also be defined as the tendency of an object to remain at constant velocity. Newton's first law is sometimes called the law of inertia.

There is probably no law of physics with which you are more familiar than Newton's first law, although you may never have thought about it before. For example, when helping to clear the table at dinner, you pick up a plate and turn quickly toward the kitchen. With a clatter the silver falls to the floor. You have applied a force to the plate, but not to the silver. Because of its inertia the silver did not move toward the kitchen with the plate, but stayed where it was until, when the plate was gone, the force of gravity acted to pull it down.

A car is stalled and you try to push it. It takes an enormous force to get it going because of its inertia. Once it is started, however, if the road is level and smooth, it continues to move slowly, and you cannot stop it easily because it is in motion and resists being slowed. Figure 2–4 illustrates some tricks which illustrate Newton's first law.

2–5 Mass is the quantitative measure of inertia. If you want to start a car by pushing it, you find that it takes a very large force to overcome its inertia. On the other hand, only a small force is needed to start a child's express wagon. The difference between the car and the express wagon is a difference in mass. The car has a large mass, whereas the wagon has a small one.

The inertia of an object provides a way of defining mass. The greater the mass of an object, the greater its tendency to keep at a constant velocity. Therefore **mass** is often defined as the quantitative measure of the inertia of an object. Like the definition for force, this is an operational definition. It tells you that you can decide which of two masses is greater by observing which one speeds up less when you apply the same force to each for the same length of time.

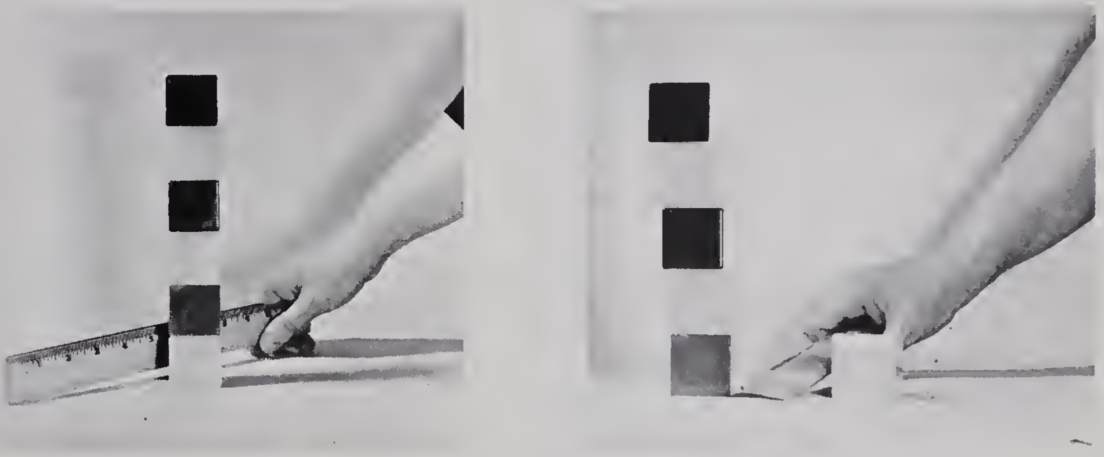
2–6 The kilogram is the mks standard of mass. The definition of mass given in the last section makes it possible for you to compare two masses, but it does not give you a way of deciding just how big either of the masses may be. The physicists' standard of mass at the present time is a platinum-iridium cylinder in a vault in Sèvres, France. It is called the international prototype *kilogram* (kg). There are copies of it in many countries (p. 7, Fig. 1–5a).

2–7 The gram was defined before the kilogram. At the time the meter was named and defined as a standard of length (see p. 18), the scientists responsible for this choice undertook to define a standard of mass as well. Furthermore, they set out to base the standard mass on the standard meter; that is, to define mass in terms of length.

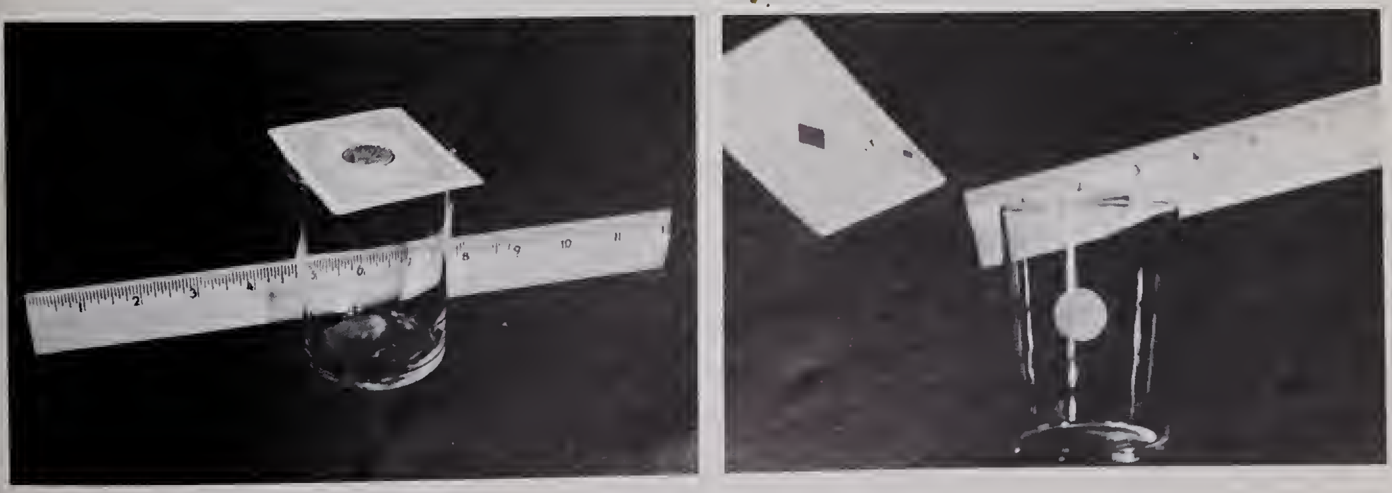
At first thought, such a definition appears impossible. But it can be done, although an intermediate step is required.

Figure 2–4 Illustrations of Newton's first law.

a. Pile up smooth blocks and give the bottom one a sharp rap with the edge of a ruler. The bottom block will sail out from under, and the rest of the stack will not be toppled but will drop down still in a pile.



b. Place a coin on a smooth card over a water glass. Give the edge of the card a sharp blow with the flat side of a ruler. The card will be knocked off the glass, but the coin will fall into it.



Every object takes up space; it has three dimensions, and each dimension can be expressed in terms of the meter. The intermediate step, then, is to select a unit of volume. When this has been done, a specified volume of a selected substance may be taken as the standard mass.

As the unit of volume, the eighteenth-century French scientists chose the cubic centimeter. As the substance, they chose pure water. They named the mass of 1 cubic centimeter (cm^3) of pure water 1 **gram.**

The choice of water was logical. Water is obtainable everywhere. It is easly purified. To be sure, its volume changes considerably with changes in temperature and atmospheric pressure, but this disadvantage was overcome by specifying the temperature and pressure at which the volume was to be measured.

Because water evaporates very readily, 1 cm^3 of water itself could not be used as a prototype gram. Platinum was the most satisfactory material available at the time. But a piece of platinum with a mass of 1 gram is only about half the size of a thin dime, much too small to be a good prototype unit of mass. A larger mass would be far easier to copy accurately.

For this reason, the committee of scientists decided to have a 1,000-gram mass of platinum constructed, rather than a 1-gram mass. They presented the prototype kilogram to the French government in the same ceremony in which the prototype meter was presented. About a hundred years later a new prototype kilogram was constructed of platinum-iridium, and adopted by scientists as the international standard of mass (p. 31).

Self Check

1. Give an operational definition of force.
2. Give an operational definition of mass.
3. If an object is pulled north by a force of 10 lb, east by a force of 15 lb, south by a force of 10 lb, and west by a force of 10 lb, what is the unbalanced force?
4. If your car is rounding a curve at a steady 40 mi/hr, are the forces acting on the car balanced or unbalanced?
5. State Newton's first law of motion.
6. How is this law different from the kind of law passed by a legislature?
7. What is inertia?
8. Why is it easier to keep a car in motion than to start one?
9. Convert (a) 3.4 kg to g; (b) 25 g to kg.

Discussion Questions

1. You are standing in a train that is slowing down. What effect does this have on your ability to stand straight up?
2. If the train moves with uniform velocity, how does its motion affect your ability to stand straight up?
3. If the train is speeding up, how does its motion affect your ability to stand straight up?
4. If you attempt to jump off a moving vehicle, in which direction should you face so as to be able to keep your balance?

Force and Acceleration

2–8 Acceleration depends on the mass and the force applied. If you push a wheeled cart, applying an unbalanced force, you accelerate it. The harder you push, the greater is the acceleration. If you apply a force to the cart when it is loaded and an equal force when it is empty, you find that the lighter cart accelerates more because of its smaller inertia. These results may be put in the form of two rules:

1. Acceleration is greater when the force is greater.
2. Acceleration is greater when the mass is less.

Experiments show that twice the force (F) acting on the same object produces twice the acceleration; three times the force produces three times the acceleration, and so on. Such a relationship is expressed mathematically thus:

$$\frac{F}{a} = \text{a constant}$$

Experiments also show that, with the same force, when the mass is reduced to half, the acceleration is doubled; when the mass is reduced to one third, the acceleration is tripled, and so on. Expressed mathematically:

$$ma = \text{a constant}$$

These two relationships can be combined in one mathematical statement:

$$\frac{F}{ma} = \text{a constant}$$

Mathematicians usually indicate a constant by the letter k. Therefore:

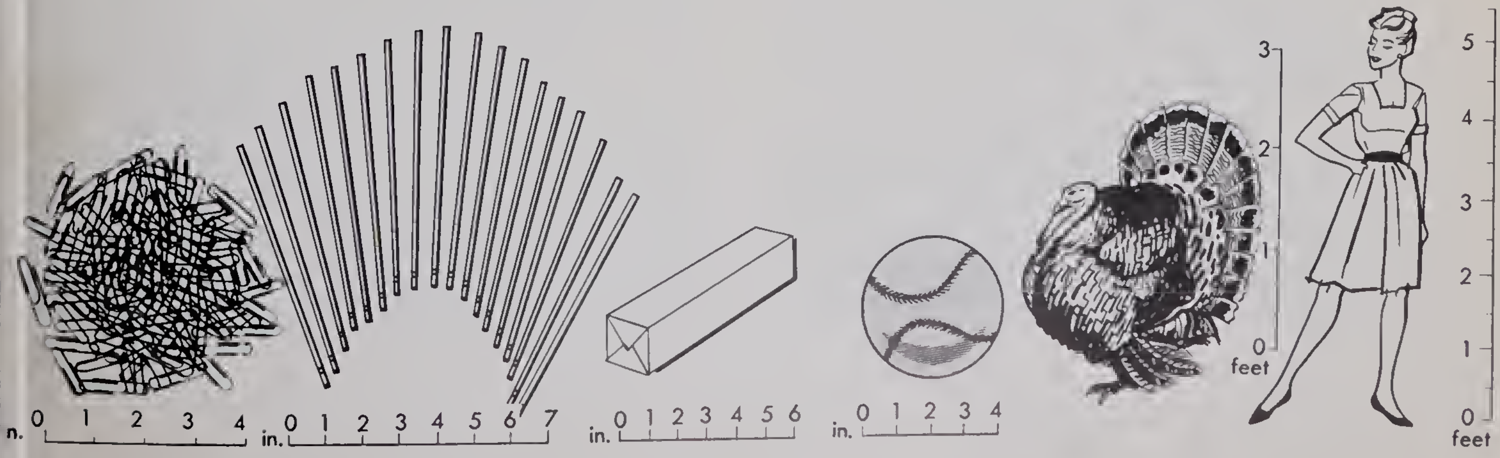
$$\frac{F}{ma} = k \quad \text{or} \quad F = kma$$

This equation is a mathematical statement of **Newton's second law**, which says that when an unbalanced force acts on an object it produces an acceleration in the direction of the force, and that the acceleration is directly proportional to the force acting and inversely proportional to the mass.

2–9 Newton's second law defines a unit of force. The units of mass, length, and time, as defined so far in this book, are called **fundamental units**. The definition of a fundamental unit is arbitrarily chosen. Men have decided to measure mass in terms of a particular object, the prototype kilogram. They could have selected some other standard, but they chose this one. Similarly, it has been decided to measure length in terms of the length of the prototype meter or of the wavelength of a particular kind of light; and to measure time in terms of the motion of the earth around the sun.

Area is measured in square meters or square feet. Velocity is measured in feet per second or meters per second. These are examples of derived units. A **derived unit** is expressed in terms of fundamental units. In the mks system of units, force is a derived unit. This unit is called the newton and is defined in terms of the second law. The **newton (N)** is the unbalanced force that will give an acceleration of 1 m/sec^2 to a mass of 1 kg. Figure 2–5 will give you an idea of the size of this unit.

Figure 2–5 How big is a newton? 180 paper clips weigh about 1 N; 18 unsharpened pencils, about 1 N; a quarter of a pound of butter, slightly more than 1 N; a softball, about 2 N; an 18-lb turkey, 80 N; a 135-lb person, 600 N.



In the equation for Newton's second law, when the mass is in kilograms, the acceleration in meters per second squared, and the force in newtons, k becomes the number 1 and can be omitted.

$$F = m \times a$$
$$1\ \text{N} = 1\ \text{kg} \times 1\ \text{m/sec}^2 = 1\ \text{kg·m/sec}^2$$

Whenever you have newtons in a problem, you can write kg · m/sec² in place of N, to see whether your units are coming out properly. See Example 1.

EXAMPLE 1

What unbalanced force is necessary to accelerate a 1000-kg car at 3 m/sec²?

Given: $m = 1000$ kg; $a = 3\ \text{m/sec}^2$

To find: F

Solution: $F = ma$

$$F = 1000\ \text{kg} \times \frac{3\text{m}}{\text{sec}^2}$$
$$= 3 \times 10^3\ \text{kg·m/sec}^2$$
$$= 3 \times 10^3\ \text{N, Answer}$$

Do It Now

Attach a screw eye to a block of wood. A 6-in. piece of 2 × 4 will do. Fasten a thread to the screw eye. Put the block on a flat surface — a table top, for example — and pull very gently on the thread. You should be able to set the block in motion and to move it across the table. Now put the block back where it was and give the thread a quick jerk. What happens? Explain both results in terms of the second law of motion.

2–10 Momentum is related to motion. If you see a large truck rolling down the highway toward you just when you have started to cross, you rush to get out of the way. What is there about the motion of this truck that makes it worthy of your respect? In the first place, it has a velocity, perhaps 20 mi/hr toward you. But the velocity alone does not make it an object to be avoided. An insect hurtling at you at 20 mi/hr would hardly cause you to get out of its way. Is it the mass, then, that is to be feared? Certainly this is not the whole story either, because if the truck were parked, you would not worry about it. Apparently, the combination of velocity with mass has a particular significance.

Newton found it very useful to multiply the mass of an object by its velocity and to use the product as a measure of the object's motion. This product he called "quantity of motion"; modern physicists call it **momentum**.

$$\text{momentum} = \text{mass} \times \text{velocity} = mv$$

There are no special units for momentum and no special name for any units. It might be kilogram · meters per second, gram · centimeters per second, or even a mixed-up expression like kilogram · kilometers per hour. Momentum is a vector quantity with its direction the same as that of the velocity.

2–11 Momentum is related to force. Newton used the idea of momentum when he described the second law. He said that the rate of change of momentum of an object is proportional to the force applied, and the change of momentum is in the direction of the force. The rate of change of momentum is the change in momentum divided by the time during which the change takes place. Thus Newton's way of expressing the law was:

$$F = \frac{\text{change in } mv}{\text{time interval}} = \frac{\Delta(mv)}{\Delta t}$$

If the mass is a constant, then

$$F = \frac{m \times \text{change in } v}{\text{time interval}} = \frac{m\Delta v}{\Delta t}$$

Since $a = \frac{\Delta v}{\Delta t}$, a can be substituted for $\frac{\Delta v}{\Delta t}$. Therefore,

$$F = ma$$

Thus $F = ma$ is a proper algebraic statement of Newton's second law if the mass does not change. At velocities approaching the speed of light, when both m and v are changing, Newton's law must be stated in terms of momentum rather than acceleration.

2–12 Newton's second law has many applications. If you were to jump from a height of 3 or 4 ft onto a hard surface, you should relax your muscles and allow your knees to bend a little as your feet hit the surface. If you do not, the force of the impact hurts your feet and jars your whole body. This illustrates Newton's second law. Your body is decelerating, or undergoing an acceleration opposite to the direction of motion. The floor is applying a force to your feet and it is this force that causes the deceleration. What does the law state? The force is proportional to the product of the mass and the acceleration. Your mass is the same no matter which way you come down, so the acceleration is the important factor here. If you come down rigidly, your body is brought to rest in a very short time and the deceleration is large. Therefore, the force is large. If you bend your knees and slow down gradually, the deceleration is smaller and so is the force.

When an elevator starts to rise suddenly, the inertia of your body produces that stomach-left-behind feeling. When it drops suddenly, you have a similar feeling. One way to think about this experience is to apply Newton's first law. In each case, your body is originally at rest, and it resists being put into motion. Your internal organs, being loosely attached, resist longer and get left behind for an instant as the rest of your body starts to move. If the elevator stops suddenly, your internal organs keep on going, and again you may feel a bit unsettled.

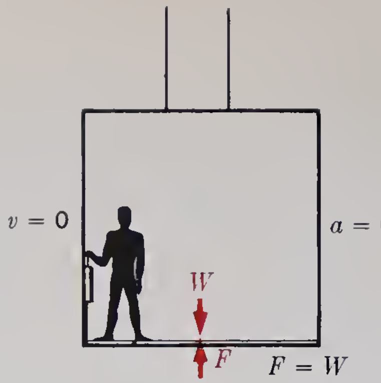
A more complete way to think about this experience is in terms of Newton's second law. Figure 2–6 on the next page illustrates this law.

Do It Now

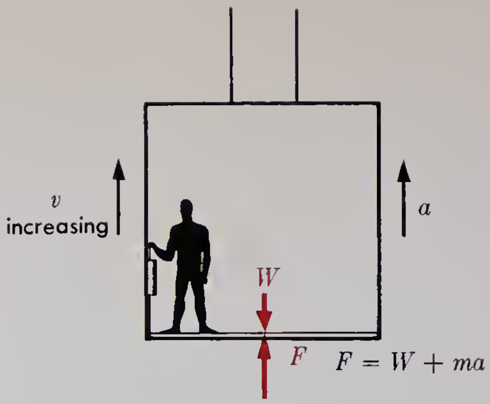
Hang a weight on a spring balance. Hold the balance until the reading is steady. Note the value of the reading. Then suddenly lift the balance. What happens to the reading when you first start the lift and later when you raise the balance with a uniform velocity? Suddenly lower the balance. What happens when you start to lower it and later when you lower it with uniform velocity? Explain your results. Figure 3–6 should help you.

Self Check

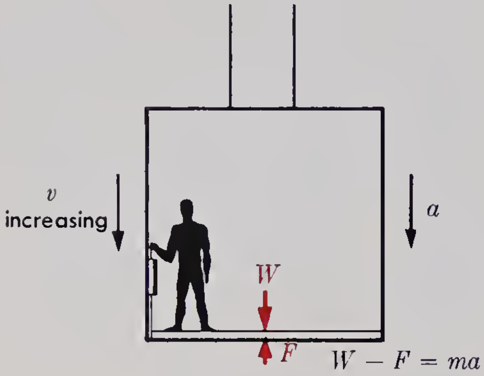
1. State Newton's second law in two different ways.
2. If you apply a force to a 3-kg cart that rolls with negligible friction, and the cart accelerates at 2 m/sec^2, what force did you apply?
3. If you apply the same force to a 6-kg cart, what will its acceleration be?
4. If you double the force applied to the 3-kg cart, what will the acceleration be?
5. Define the newton.
6. What is the momentum of a 5.0-kg ball rolling with a velocity of 3.0 m/sec?
7. What is the direction of momentum?
8. If a ball is rolling toward the north, and a force is applied to it toward the west, what is the direction of the acceleration?
9. A moving cart is pushed from behind with a force of 10 N. The retarding forces of friction and air resistance equal 10 N. No other horizontal forces act on the cart. If it has a mass of 2 kg, what is its acceleration?



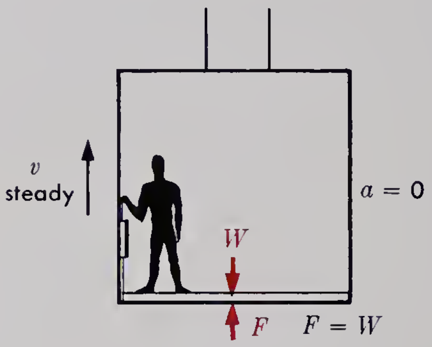
a. If the elevator is not moving, its floor pushes on your feet with a force (F) equal to your weight (W). These forces balance. You are in equilibrium.



b. While the elevator accelerates, the floor pushes on your feet with a force equal to your weight (W) plus a force for acceleration (ma) The downward and upward forces are unbalanced.



c. When the elevator accelerates downward, the force of your weight is greater than the supporting force of the elevator. Therefore you accelerate downward. $W - F$ is the unbalanced force causing the acceleration.



d. When the elevator moves with constant velocity, no force is required for acceleration. Therefore the elevator pushes on you only with a force equal to your weight. The forces balance. You are in equilibrium.

e. If the elevator cable snaps and the elevator falls freely, both it and you are falling at the same rate. The upward force on your feet is 0. Your weight, acting downward, makes you fall, but because there is no pressure on the soles of your feet, you have a feeling of weightlessness. This is a kind of feeling that space ship passengers have when their ship is coasting through space.

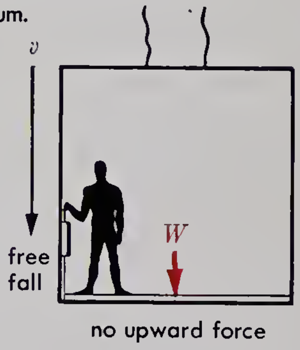


Figure 2–6 Newton's second law in an elevator.

Problems

A

1. What will be the acceleration of a 1000-kg car if an unbalanced force of 800 N is applied?

2. An unbalanced force of 150 N is applied to a boat which is accelerated at 0.50 m/sec^2. What is the mass of the boat?

3. A pony with a mass of 300 kg pulls a cart with a mass of 1000 kg. With what force will the pony have to pull on the cart if he is to accelerate at 2.0 m/sec^2? Assume no friction in the wheels.

4. With what force will the pony's hoofs have to push on the ground?

5. What is the momentum of a 1000-kg car moving at 20 m/sec?

6. A car with a mass of 1500 kg has a momentum of 24,000 kg · m/sec. What is the magnitude of its velocity?

7. A 3000-lb automobile accelerates from rest at 10 ft/sec^2 for 5.0 sec. What is its momentum at the end of that time?

8. A 6.0-g bullet traveling at 300 m/sec goes through a block of wood and emerges at 100 m/sec. What is its change in momentum?

B

9. A freight engine of mass 20,000 kg accelerates from rest up to a velocity of 2.0 m/sec in 5.0 sec. If it is pulling a train of 20 cars, each with a mass of 10,000 kg, what is the force in the coupling between the engine and the first car?

10. What is the force in the coupling between the 10th and 11th cars of the train in Problem 9?

Discussion Questions

1. Why is a car that crashes into a stone wall damaged more than one that crashes into a barrier made of steel cables?
2. Show that Newton's first law is actually a special case of the second.
3. Why does a baseball sting your hand if you hold your hand rigid, but does not if you let your hand "give" while catching the ball?
4. Compare the tension in the cable between a tugboat and the first barge it is accelerating with the tension in the cable between the first and second barges.

The Force of Gravity

2–13 Newton formulated the law of universal gravitation. What makes an apple fall to the earth? Newton is supposed to have started thinking about gravitational forces when he noticed a falling apple. Whether or not the apple story is true, Newton did a great deal of thinking and came up with ideas that completely changed man's concept of the universe. Here is his line of reasoning:

An apple falls because the earth attracts it. (This was not a new idea.) Perhaps the apple attracts the earth, too. (This was certainly a new idea.) Perhaps apples attract each other. Perhaps all objects attract each other. (Here he was getting far from the ideas scientists had had up till then. Next he took a big step.) Perhaps the force of attraction, the gravitational attraction between various objects, works even at very great distances; thus the earth and the moon attract each other, the sun and the planets attract each other, possibly even the sun and the stars attract each other.

Why was this last such a big step? Because until then, people had supposed that the laws governing the behavior of matter on the earth were different from those governing the behavior of heavenly bodies. Newton was talking about *universal* gravitation.

If you put two balls near each other on a level table, they do not roll toward each other. However, Newton believed that they attract each other. He realized that if there were a force pulling them together it must be extremely small. The force pulling the apple to the earth, on the other hand, is relatively large. Newton's first quantitative hypothesis about the force of gravity was that it depends upon the masses involved. The earth pulls on the apple with a fairly large force because the earth has a large mass, even though that of the apple is small. The two balls pull on each other with a small force because their masses are small. Therefore, he said that the force between two objects is proportional to the product of their masses.

Newton's second quantitative hypothesis about the force of gravity was that it depends on the distance between the masses. He proposed that the force between two masses was inversely proportional to the square of the distance between their centers of gravity. These two relationships can be stated thus:

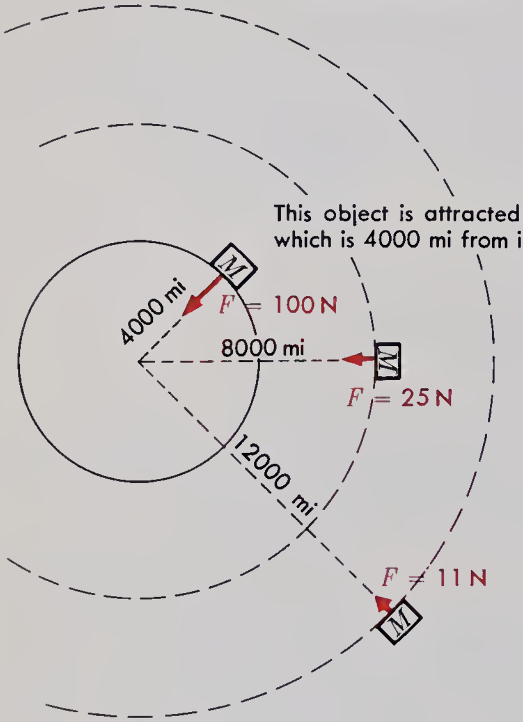
$$F \propto \frac{m_1 m_2}{s^2}$$

where m_1 and m_2 are the masses, and s is the distance between their centers. The symbol $\propto$ means "is proportional to." It may be replaced by an equals sign and a constant. It is customary to use a capital G to represent the constant:

$$F = G\frac{m_1 m_2}{s^2}$$

Figure 2–7 Newton's law of universal gravitation.

a. The effect of distance on gravitational forces.

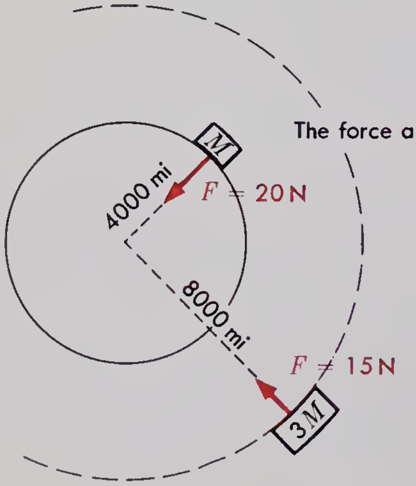


This object is attracted to the earth with a force of 100 N at the earth's surface, which is 4000 mi from its center.

The same object at this point is two times as far away from the center of the earth. The force is $(1/2)^2$ or 1/4 as much and is therefore equal to 25 N.

The object is now 3 times as far away, and the force is therefore $(1/3)^2$ or 1/9 as much as it was originally—approximately 11 N.

b. The combined effect of distance and mass on gravitational attraction.



The force acting on mass M at the surface of the earth is 20 N.

This mass is 3 times as great, so the force is multiplied by 3. However, the mass is also 2 times as far away. Therefore the force is divided by 2^2 or 4. The combined effect of the change in mass and distance is to make the force 3/4 times as great, or 15 N.

G is called the **constant of gravitation**, or the gravitational constant. It is entirely different from the g that represents acceleration of gravity. The value of G was determined about 100 years after Newton's work. It is $6.67 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}$.

Newton's law of universal gravitation (which is not one of his three laws of motion) can be stated thus: Every mass in the universe attracts every other mass with a force that is directly proportional to the product of the masses and inversely proportional to the square of the distance between their centers of gravity. This law is illustrated in Fig. 2–7.

The force of gravity extends into space. This force exists between the moon and the earth, between the earth and the sun, and among all the objects in the solar system and the entire universe. The gravitational attraction between the earth and the sun keeps the earth in its nearly circular orbit around the sun. A similar situation applies to the moon's orbit around the earth. The moon's gravitational pull on the earth and, to a lesser extent, that of the sun, produce the ocean tides, as illustrated in Fig. 2–8.

2–14 Newton used the moon to test the law of gravitation. When Newton had proposed his equation for the force of gravity, he proceeded to test his hypothesis. He used the moon and the earth as his "test spheres." The moon, he said, would travel in a straight line if there were no unbalanced force acting upon it (the first law). Instead of traveling in a straight line, it curves around the earth. Therefore some unbalanced force is giving it an acceleration toward the earth. (See Fig. 1–6c.)

As stated in Sec. 1–9, the acceleration of any object moving in a curved path is:

$$a = \frac{v^2}{r}$$

Newton knew the radius and length of the moon's path around the earth, and the time required for one revolution of the moon. Therefore he could calculate v and then could find the acceleration. If you do this, using the modern values of the distance and time, you find that the acceleration of the moon toward the earth is $0.00272\ \mathrm{m/sec^2}$.

How does this acceleration compare with the acceleration of an apple falling to earth? If you divide $9.8\ \mathrm{m/sec^2}$ by 0.00272, you find that the result is nearly 3600. Notice that, so far, Newton had not used his law of gravitation at all. What he had learned was that the acceleration of a falling body near the earth is 3600 times as great as the acceleration of the moon.

Now Newton was ready to test his law. If by using the law of universal gravitation he could prove the acceleration of a falling apple toward the earth to be 3600 times as great as the acceleration of the moon toward the earth, then he would think it very likely that the law was true. Here is how he did it:

First think about the falling apple. It is accelerating because of the gravitational pull of the earth:

$$\text{force between earth and apple} = G\frac{m_E m_A}{r^2}$$

where m_A is the mass of the apple, and r is the distance between the center of the apple and the center of the earth, or the radius of the earth. This force gives the apple its

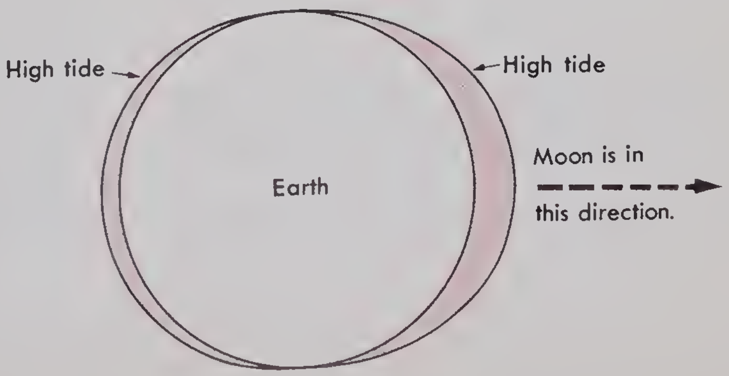


Figure 2–8 The moon attracts the water on the near side of the earth, causing a high tide in that area. The moon also attracts the earth itself away from the overlying water on the opposite side of the earth, resulting in a slightly smaller high tide there.

acceleration g and must therefore be equal to $m_A g$:

$$m_A g = G\frac{m_E m_A}{r^2}$$

$$g = G\frac{m_E}{r^2}$$

Next think about the moon:

$$\text{force between the earth and the moon} = G\frac{m_E m_M}{R^2}$$

where m_E and m_M are the masses of the earth and the moon, respectively, and R is the distance between their centers, or the radius of the orbit of the moon. This unbalanced force gives the moon an acceleration, a_M.

$$\text{force to accelerate the moon} = m_M a_M$$

The force to accelerate the moon is supplied by the pull of the earth. Therefore:

$$m_M a_M = G\frac{m_E m_M}{R^2}$$

$$a_M = G\frac{m_E}{R^2}$$

Now you have an equation for the acceleration of the moon, based on the law of gravitation, and an equation for the acceleration of the apple, also based on the law of gravitation. Divide one by the other:

$$\begin{aligned}\frac{g}{a_M} &= G\frac{m_E}{r^2} \div G\frac{m_E}{R^2}\\ &= \frac{Gm_E}{r^2} \times \frac{R^2}{Gm_E}\\ &= \frac{R^2}{r^2} = \left(\frac{R}{r}\right)^2\end{aligned}$$

The radius of the moon's orbit (R) is approximately 240,000 miles. The radius of the earth (r) is approximately 4,000 miles. Therefore $\frac{R}{r}$ is equal to 60; the square of this fraction is 3600. Newton's hypothesis about universal gravitation passed the test.

2–15 Newton's law has been checked many times.

Newton could not measure G because the force between two objects on the surface of the earth is very small, and he did not have delicate enough instruments to measure this force. Two cars with their centers 10 feet apart would exert forces on each other of less than one ten thousandth of an ounce. Two 60,000-ton air-craft carriers, separated by 100 yards, would exert gravitational forces on each other of approximately five pounds.

However, forces much smaller than this have been measured between masses in the laboratory, and thus Newton's law has been checked many times and the value of G determined.

2–16 Weight is a force.

Weight is the resultant of all the gravitational forces on an object. When you are at sea level, you are closer to the center of the earth and you weigh more than when you are at the top of a mountain. On the moon, your weight would be largely due to the force with which the moon pulled on your body. Since the moon has a much smaller mass than the earth (about 1/81), and the distance from the moon's surface to its center of gravity is considerably less than the corresponding distance on earth (about 27%), you would weigh only about one sixth of your present weight, and you would find it very easy to leap great distances. On Jupiter, because of its immense mass, you would weigh approximately two and a half times what you do on earth. An object weighs more at the earth's poles than it does at the equator; it is some 13 mi closer to the earth's center at the poles than at the equator.

Thus weight is not a good physical standard; it varies from place to place. Mass, on the other hand, is constant, at ordinary velocities even when moved from place to place.

The orbit of a satellite is influenced by the fact that the earth is not a perfect sphere. Studies of satellite orbits can be used to determine variations in the shape of the earth. They have shown that the earth not only bulges at the equator, but is very slightly wider in the southern hemisphere than in the northern.

2–17 The kilogram of force is used in weighing. When you hang a load on a spring balance in the laboratory, you do not read the weight in newtons. Instead you read it in grams or kilograms. When you weigh an object in kilograms, you are using the *kilogram of force* (kgf). This is not the same thing as the kilogram of mass. A kilogram of force is the force with which the earth pulls on a mass of 1 kg under certain circumstances. This "under certain circumstances" is important, because the weight of a body depends upon where it is, as you have seen. If you go up in a plane, your weight decreases because you are farther from the center of the earth. Your mass, however, remains the same.

The accepted definition of the **kilogram of force** is that it is the weight of the international standard kilogram when it is in a place where g is 9.80665 m/sec^2. An easier definition, and one almost as accurate, is that a kilogram of force is the weight of a 1-kg mass at sea level and 45° latitude, north or south.

Mass and weight are not the same. Mass measures the inertia of an object and is constant for all practical purposes. Weight measures the force of attraction between the object and the earth or other large object. It varies from place to place. On the surface of the earth, the variation is about one percent. In space, variations are much greater.

The pound is a unit of force. It is legally defined in the British Commonwealth countries in this way:

$$1 \text{ lb} = 0.453\,592\,37 \text{ kgf}$$

Ordinarily this is rounded off to 0.454 kgf. One kgf is equal to 2.20 lb. See Example 2.

EXAMPLE 2

Convert a weight of exactly 2000 lb to kgf.

Solution:

$$\begin{aligned} W &= 2000 \text{ lb} \\ &= 2000 \text{ lb} \times 1 \\ &= 2000 \text{ lb} \times \frac{0.454 \text{ kgf}}{1.00 \text{ lb}} \\ &= 908 \text{ kgf, Answer} \end{aligned}$$

2–18 Force units are related. The newton is a force unit; the weight of a kilogram can also be used as a force unit. How are these two related?

Think about a 1-kg mass as it falls. In this case, F is the weight, which may be represented by W. The acceleration is g, because the object is falling. The force equation then becomes:

$$W = mg$$

Substituting values:

$$\begin{aligned} W &= 1 \text{ kg} \times 9.8 \text{ m/sec}^2 \\ &= 9.8 \text{ kg·m/sec}^2 \\ &= 9.8 \text{ N} \end{aligned}$$

Thus the weight of a 1-kg mass at the surface of the earth is 9.8 N, and therefore 1 kgf must equal 9.8 N. More precisely:

$$1 \text{ kgf} = 9.80665 \text{N}$$

If you have made some measurements in kilograms of force, you can avoid having to change them to newtons before using $F = ma$, if you first make a change in the equation. Since $W = mg$, then $m = W/g$. Substitute this in $F = ma$ and you have:

$$F = \frac{Wa}{g}$$

2–19 Inertial mass is proportional to gravitational mass. You can find out whether two masses are equal by seeing whether both receive the same acceleration when equal forces are applied. However, this is not the usual way to compare masses. Ordinarily you do it by weighing them. If the force of attraction of the earth for each of them is the same when both are in the same location, then you say that they have equal masses.

Actually you have not measured their masses at all. What you have done is to compare the forces acting on them. However, the remarkable fact is that whenever you do this you come out with the right answer. Apparently the mass as measured by inertia (**inertial mass**) is quantitatively equal to mass as measured by gravitational attraction (**gravitational mass**).

Perhaps this does not seem remarkable to you because you are used to the idea. This equality does not apply to other forces, however. For example, one magnet may be much stronger than another, despite the fact that both have the same inertial mass.

Galileo discovered that falling objects of different masses accelerate at the same rate. They do so because of the equivalence of gravitational and inertial masses. If one object, X, has twice as much gravitational mass as another, Y, when they fall, X is accelerated by twice as great a force. However, because X also has twice as great an inertial mass, its resistance to acceleration is also twice as great. Therefore X and Y accelerate at the same rate.

2–20 Various systems of mass and force units are in use. So far the discussion of mass and force units in this chapter has been limited to the mks system. Life would be much simpler if the world had a single system of units, but this is not the case. The metric system has two sets of units, the mks and cgs. There are also English units. Here is a summary of the units used in this book.

Absolute System of Units

In these systems, mass is considered to be a fundamental quantity and force a derived quantity.

mks system (meter-kilogram-second)

The unit of *mass* is the **kilogram**, equal to the mass of the standard kilogram in France. Any object possessing the same inertia as the standard kilogram has a mass of 1 kg.

The unit of *force* is the **newton**, which is the force that gives an acceleration of 1 m/sec^2 to a mass of 1 kg.

$1\text{ N} = 1\text{ kg}\cdot\text{m/sec}^2 \qquad 9.81\text{ N} = 1\text{ kgf}$

cgs system (centimeter-gram-second)

The unit of *mass* is the **gram** (**g**), defined as exactly 0.001 of the mass of the standard kilogram.

The unit of *force* is the **dyne**, defined as the force that gives an acceleration of 1 centimeter (cm)/sec^2 to a mass of 1 g. This is an extremely small force. One paper clip has a weight of approximately 500 dynes. $1\text{ dyne} = 1\text{ g}\cdot\text{cm/sec}^2$.

$981\text{ dynes} = 1\text{ gf.}$*

Gravitational System of Units

In a gravitational system, force is considered to be a fundamental quantity and mass a derived quantity.

British engineering system

The unit of *force* is the **pound**. The pound of force is defined as the *weight* of 0.45359237 of the standard kilogram when the weighing is done at a place where the acceleration of gravity is 32.174 ft/sec^2. For all practical purposes such a location is at 45° N or S latitude, at sea level. Notice that the same standard object, the international kilogram in

---

* Since the kilogram of force is measured where $g = 980.665\text{ cm/sec}^2$, the gram of force actually equals 981 dynes to 3 significant digits. However, you may use 980 as a reasonably accurate figure.

France, can be either a standard for mass or a standard for force.

The unit of *mass* is the **slug**. This is the mass that will be given an acceleration of 1 ft/sec^2 by a force of 1 lb. Since a force of 1 lb gives an acceleration of approximately 32 ft/sec^2 to a mass of 1 lb, the slug must be equal to approximately 32 lb of mass. Rewriting $F = ma$ as $m = F/a$, you can see that

$$1 \text{ slug} = 1\frac{\text{lb}}{\text{ft/sec}^2} \text{ or } 1\frac{\text{lb}\cdot\text{sec}^2}{\text{ft}}.$$

From the point of view of the laws of motion, one of these systems is as good as the next. $F = ma$ is true for all of them.

So is $W = mg$. So is $F = \frac{Wa}{g}$.

For scientific work the cgs system was the favorite for a long time. It is now being supplanted by the mks system because the size of the newton is such that human beings can experience it in daily life, and because electrical units in this system are also of a practical size.

For engineering work in English-speaking countries, the British engineering system is the favorite, and it is also, in a slightly modified form, the one used in daily life. You may never have heard of the slug, but engineers use it. However, you can avoid having to work with it if you use the second-law equation in the form: $F = \frac{Wa}{g}$.

Study the table below and the examples on the next page.

Table 2–1 COMPARISON OF FORCE AND MASS UNITS IN VARIOUS SYSTEMS

System	*Force*	*Mass*
mks	Newton (N) $= \frac{\text{kg}\cdot\text{m}}{\text{sec}^2}$ Approximately equal to the weight of 18 new lead pencils or 180 ordinary paper clips 1 N = 3.6 oz 1 kgf = 9.8 N	Kilogram (kg) Approximately equal to the mass of 176 new lead pencils or 1760 ordinary paper clips
cgs	Dyne (dyn) $= \frac{\text{g}\cdot\text{cm}}{\text{sec}^2}$ Approximately equal to the weight of 0.002 paper clip 1 gf = 980 dyn	Gram (g) Approximately equal to the mass of two paper clips
British engineering	Pound (lb) Approximately equal to the weight of 800 paper clips or 80 pencils	Slug $= \frac{\text{lb}\cdot\text{sec}^2}{\text{ft}}$ Approximately equal to the mass of 26,000 paper clips or 2600 pencils 1 slug = 32 lb of mass

EXAMPLE 3

What force is necessary to accelerate a 200-g ball at 80 cm/sec^2?

Given: $m = 200\text{ g} \qquad a = 80\text{ cm/sec}^2$

To find: F

Solution:

$$\begin{aligned} F &= ma \\ &= 200\text{ g} \times 80\text{ cm/sec}^2 \\ &= 1.6 \times 10^4\text{ g}\cdot\text{cm/sec}^2 \\ &= 1.6 \times 10^4\text{ dynes, Answer} \end{aligned}$$

EXAMPLE 4

What force is necessary to accelerate a 2000-lb car at 50 ft/sec^2? Solve using British engineering system.

Given: $m = 2000\text{ lb} \times \dfrac{1\text{ slug}}{32\text{ lb}} = 62\text{ slugs}$

$a = 50\text{ ft/sec}^2$

To find: F

Solution:

$$\begin{aligned} F &= ma \\ &= 62\text{ slugs} \times 50\text{ ft/sec}^2 \\ &= 3.1 \times 10^3\text{ slug}\cdot\text{ft/sec}^2 \end{aligned}$$

But $1\text{ slug} = 1\,\dfrac{\text{lb}\cdot\text{sec}^2}{\text{ft}}$. Therefore

$$\begin{aligned} F &= 3.1 \times 10^3\,\frac{\text{lb}\cdot\text{sec}^2}{\text{ft}} \times \frac{\text{ft}}{\text{sec}^2} \\ &= 3.1 \times 10^3\text{ lb, Answer} \end{aligned}$$

EXAMPLE 5

What force is necessary to accelerate a 2000-lb car at 50 ft/sec^2? Solve using British engineering system but without using slugs.

Given: $W = 2000\text{ lb}$

$a = 50\text{ ft/sec}^2$

To find: F

Solution:

$$\begin{aligned} F &= \frac{Wa}{g} \\ &= \frac{2000\text{ lb} \times 50\text{ ft/sec}^2}{32\text{ ft/sec}^2} \\ &= 3.1 \times 10^3\text{ lb, Answer} \end{aligned}$$

Self Check

1. Why did Newton's law of gravitation represent a radical change in the way of thinking about the universe?
2. Does a 1-kg weight in the physics laboratory exert a force on the sun?
3. If you move an object from the earth to the moon, what happens to its weight? Why?
4. Compare your weight in Calgary with your weight at the top of Sulphur Mountain, in Banff.
5. Compare your mass in Calgary with your mass at the top of Sulphur Mountain, in Banff.
6. Is it possible to measure the gravitational attraction between objects small enough to put into a schoolroom?
7. Compare your weight at noon when the moon is new with your weight at midnight when the moon is new.
8. What is the weight in newtons of a 10-kg mass?
9. What is the weight in kilograms of force of a 10-kg mass?
10. What is the distinctive characteristic of an absolute system of units?
11. Define the kilogram of force.
12. What is the unit of mass in the British engineering system?
13. Give an equation for the weight of any object when the mass is known.
14. Give an equation expressing Newton's second law without mass units.

Problems

A 1. An object has a weight of 720 N at the surface of the earth. What will it weigh when it is 2000 mi above the surface of the earth? Take the radius of the earth as 4000 mi.

2. If you weigh 100 lb on the earth, what would you weigh on a planet with a mass 300 times that of the earth and a radius 10 times that of the earth? (Data roughly similar to Jupiter.)

3. Find the weight in newtons of a 300-kg mass.

4. An object weighs 576 lb. What is its mass in slugs?

5. What is the acceleration of a 2000-kg mass if it is pulled by an unbalanced force of 100 kgf?

6. What is the acceleration of a 100-lb box if the unbalanced force applied is 5.0 lb?

7. What force is required to stop a 2400-lb car in 30 sec if the car is traveling at 60 mi/hr?

B

8. A flier is accelerated upward with an acceleration equal to 8.00 g. Find his acceleration in (a) m/sec^2; (b) ft/sec^2. (c) If he weighs 150 lb, what is the force that accelerates him? (d) How many times his weight is this force? (e) What is the total upward force on his body?

9. The first United States earth satellite rose to an altitude of 53 mi in 145 sec. With its missile assembly it weighed 65,000 lb. Assuming that it accelerated uniformly, compute the acceleration and the force necessary to give it this acceleration. It is reported that the first-stage rocket had a thrust of 78,000 lb. How do you account for the fact that your result does not agree with this?

10. The radius of the earth is approximately 6,400,000 m. Use this fact plus the fact that the gravitational pull of the earth on a 1-kg mass at its surface is 9.8 N to find the mass of the earth.

Discussion Questions

1. If Newton's law of gravitation is true, then if you move a book from one side of a table to the other, this should affect the movement of a star billions of miles away. Could this effect be measured? What reasons are there for believing that you probably do influence the stars when you move?
2. In addition to the variations in weight of an object due to altitude and latitude changes, there are local variations not caused by changes in the distance to the center of the earth. What might cause these variations?
3. Why is an experiment to measure G sometimes called "weighing the earth?"

Actions Produce Reactions

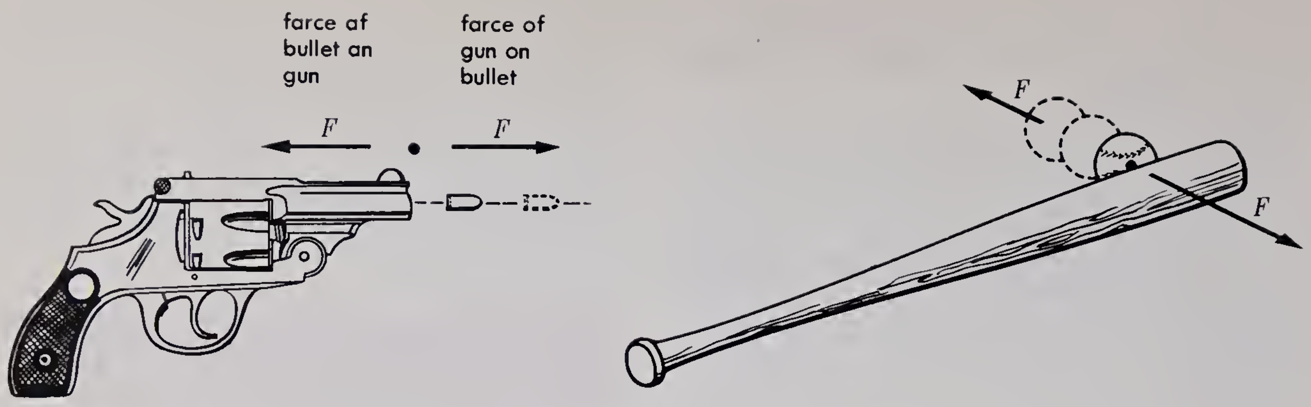
2–21 Every force is accompanied by an opposite force. When you hit a ball with a bat, the bat exerts a force on the ball. At the same time, the ball exerts a force on the bat. These two forces are equal in magnitude but opposite in direction.

If you suspend a picture from a picture hook, the wire exerts a downward force on the hook. The hook pulls upward on the wire with an equal force.

These are examples of **Newton's third law of motion**, which states that if one object applies a force to another, the second object applies an equal and opposite force to the first object. This law is sometimes abbreviated thus: For every action there is an equal and opposite reaction.

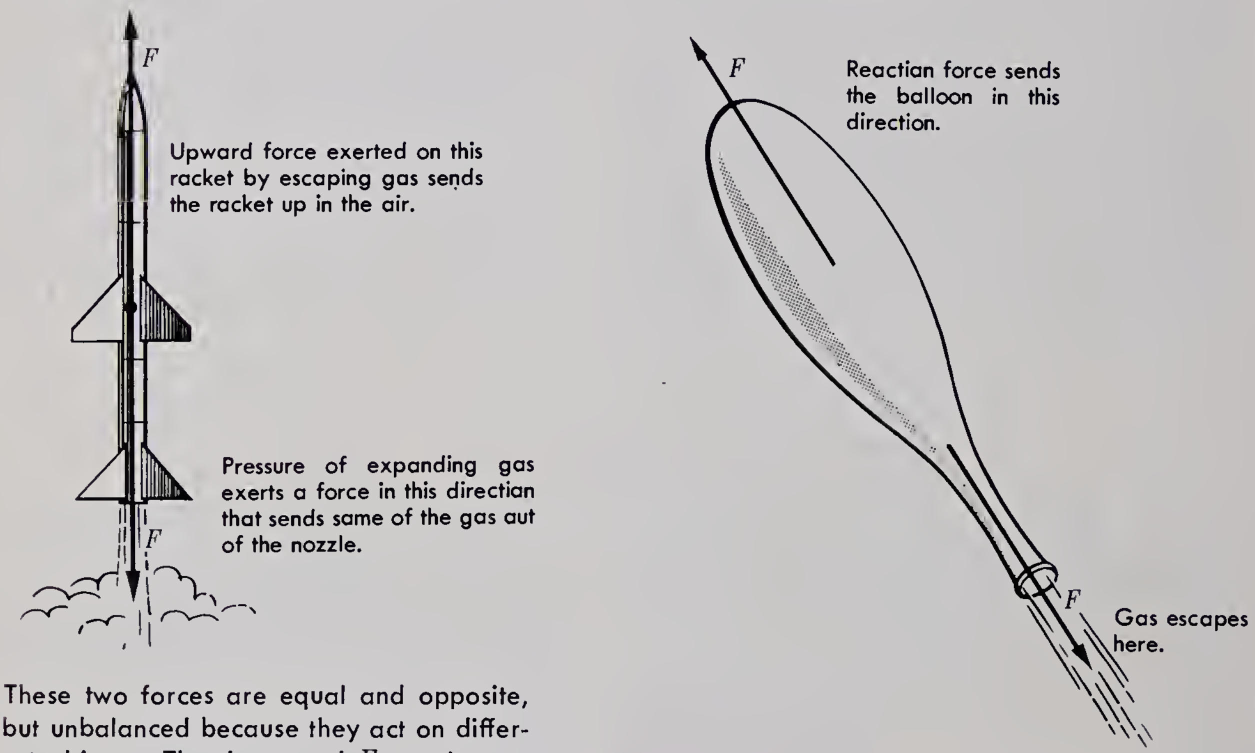
Another example is the man on page 26 wearing a rocket-powered jump belt. As a result of the burning inside the rockets, gas is pushed out at high velocity. The escaping gas pushes on the rockets, forcing them and the man carrying them up into the air. If the force of the expanding gas on the rocket equals the force of the rocket on the gas, how can the rocket get the unbalanced force for acceleration? If the two forces are equal and opposite, why don't they cancel each other out and produce equilibrium?

The answer to this question is that the two forces may be equal, but because they act on different objects, the forces are not balanced. The force of the rocket on the gas is an unbalanced force accelerating the



a. The exploding gunpowder exerts a force that accelerates the bullet out the barrel of the gun. The bullet exerts a backward force that the hunter feels as a "kick."

b. When a bat hits a ball, the bat exerts a force on the ball and the ball exerts an equal and opposite force on the bat. These forces are not balanced because they act on different objects.


F
Upward force exerted on this rocket by escaping gas sends the rocket up in the air.
Pressure of expanding gas exerts a force in this direction that sends some of the gas out of the nozzle.
F
F
Reaction force sends the balloon in this direction.
F
Gas escapes here.

c. These two forces are equal and opposite, but unbalanced because they act on different objects. The downward F accelerates the gas. The upward F accelerates the rocket.

d. You can make a simple rocket by blowing up a balloon and then letting it go.

Figure 2–9 Newton's third law of motion.

gas downward. The force of the gas on the rocket is another unbalanced force, accelerating the rocket upward. Figure 2–9 shows examples of third-law forces.

2–22 The third law applies to momentum as well as force. Consider the bullet and gun of Fig. 2–9. According to the third law:

$$\frac{}{}\begin{array}{c}\text{magnitude of force}\\ \text{of gun on bullet}\end{array} = \begin{array}{c}\text{magnitude of force}\\ \text{of bullet on gun}\end{array}$$

The effect of the first force is to accelerate the bullet forward; of the second and equal force, to accelerate the gun backwards. Newton's second law states that the rate of change of momentum is proportional to the force (p. 34):

$$F = \frac{\Delta(mv)}{\Delta t}$$

Substituting this in the equation at the bottom of the previous page:

$$\frac{\Delta(mv) \text{ of bullet}}{\Delta t} = \frac{\Delta(mv) \text{ of gun}}{\Delta t}$$

The time interval is the same for the bullet and for the gun because the equal and opposite forces act only while the bullet is inside the barrel of the gun. Therefore the equation above is simplified to:

$$\Delta(mv) \text{ of bullet} = \Delta(mv) \text{ of gun}$$

Thus when two bodies interact, the change of momentum of one body is equal and opposite to the change of momentum of the other. See Example 6 at the right.

Note that it is not necessary to put all units in the same system. The masses are in grams (cgs units) and the velocities in m/sec (mks units). The only requirement is that both masses be in the same units and that both velocities be in the same units.

Momentum is a vector quantity, as was pointed out earlier. In the case of the bullet and gun the two momenta are equal in magnitude and opposite in direction. If they are added, the sum is zero. Before the explosion of the gunpowder, the momentum was zero. After the explosion, the sum of the momenta is zero. This illustrates one of the important laws of physics, the **law of conservation of momentum**. In any group of objects that act upon each other, the total momentum before the action equals the total momentum after the action. This is true even when the objects are moving at the start.

In the case of the bullet and the gun the bullet is very small compared with the gun. Therefore the gun has a very small velocity compared with that of the bullet. It is interesting to think of the earth and yourself as the gun and bullet. When you jump, you exert a force down on the earth. The earth exerts an equal and opposite force upward. This force accelerates you and gives you a momentum.

But what about the earth? Since you exerted an unbalanced force upon it, it must be accelerated away from you and must have a momentum equal to yours. The earth is so enormous compared with you that its velocity is too small to measure, but there is no doubt that you move it whenever you jump. The gravitational force between you and the earth pulls you together again. You and the earth fall toward each other. From now on, whenever you walk, run, or jump, you can remind yourself that you are pushing the earth around.

EXAMPLE 6

A bullet with a mass of 10 g is shot horizontally from a gun with a mass of 2.0 kg. The muzzle velocity of the bullet with respect to the earth is 500 m/sec. What is the recoil velocity of the gun if the gun is mounted on frictionless, massless rollers?

Given: Mass of bullet = 10 g
Mass of gun = 2.0 kg
= 2.0×10^3 g
Final v of bullet = 500 m/sec
Initial v of bullet = 0
Initial v of gun = 0

To find: Final v of gun

Solution: $\Delta(mv)$ of gun = $\Delta(mv)$ of bullet

$$2.0 \times 10^3\text{ g} \times (v - 0) = 10\text{ g} \times \left(500\,\frac{\text{m}}{\text{sec}} - 0\right)$$

$$v = \frac{10\text{ g}}{2.0 \times 10^3\text{ g}} \times \frac{500\text{ m}}{\text{sec}}$$

$$= 2.5\text{ m/sec, Answer}$$

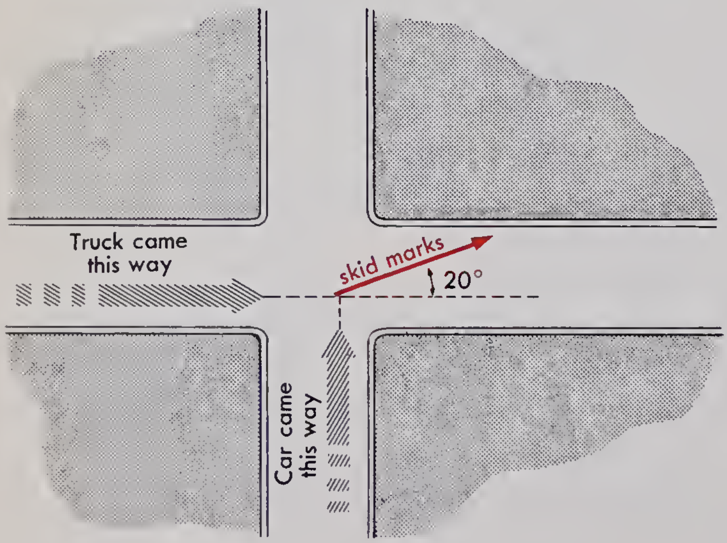
2–23 The law of conservation of momentum applies to collisions. Imagine that a 4.0-ton truck and a 1.0-ton car have collided. The two vehicles become entangled and skid off the road together. Fortunately the two drivers are not hurt. Instead they are spoiling for a fight as they leap to the ground. As the police arrive, each indignantly protests his innocence. "I was doing 30 and this hot-rod comes tearing up out of nowhere. He must have been doing 60," says the truck driver. "That's a good one," says the car driver. "I was the one doing 30 and he was doing 60, and if you want proof, just look at the skid marks." The police plotted the diagram shown in Fig. 2–10 below.

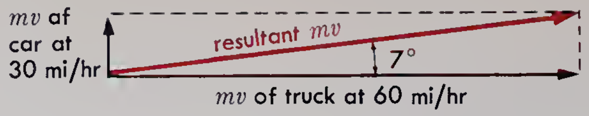
Later the police used the law of conservation of momentum to check on the facts. They knew that the sum of the two momenta before the collision is equal to the momentum after the collision. First they figured the original momenta:

If the car driver were telling the truth:

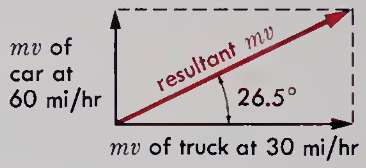
Car's momentum was
1.0 T × 30 mi/hr = 30 T·mi/hr
Truck's momentum was
4.0 T × 60 mi/hr = 240 T·mi/hr

Figure 2–10 This diagram shows what the police were able to learn about the collision of a truck and a car.

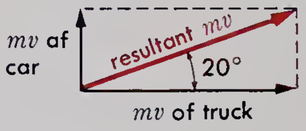




a. This would be the situation if the car driver were telling the truth.



b. This would be the situation if the truck driver were telling the truth.



c. This drawing, using the correct angle, shows that the truck's momentum was 2.7 times that of the car. Therefore the truck's velocity was 0.68 that of the car. From this diagram it is impossible to determine the true velocities. One velocity must be known in order to calculate the other.

Figure 2–11 Which driver was lying about the accident?

If the truck driver were telling the truth:

Car's momentum was
1.0 T × 60 mi/hr = 60 T·mi/hr
Truck's momentum was
4.0 T × 30 mi/hr = 120 T·mi/hr

Remembering that momentum is a vector, they drew the vectors for each possibility. The momentum after the collision was equal to the vector sum. The diagrams are shown in Fig. 2–11. If the car driver had told the truth, the skid marks should have been at an angle of 7°. If the truck driver had told the truth, the skid marks should have been at an angle of 26.5°. Obviously each man was dressing up the story a bit to favor himself. Finally the police drew the last diagram of Fig. 2–11 and discovered that the momentum of the truck had been about 2.7 times the momentum of the car.

momentum of truck = 2.7 × momentum of car
4.0 T × velocity of truck
= 2.7 × 1.0 T × velocity of car
velocity of truck = 0.68 × velocity of car

Therefore they knew that the truck driver came nearer to telling the truth than the other man. The truck was traveling more slowly than the car. They did not have enough information to determine the exact velocity of either vehicle.

Calculations like these are important also to nuclear physicists. In special photographs like those on pages 96 and 122 (Chapters 4 and 5), they observe the tracks made by tiny particles when they collide. Sometimes the mass and speed of one of the particles both before and after the collision are known. Then the momentum change experienced by the other particle can be calculated. Using also other information gained from the length and thickness of the tracks, scientists are sometimes able to determine the mass and velocity of the second particle.

2–24 Objects moving in a curved path illustrate all three laws of motion. If you tie a heavy ball to the end of a string and whirl it in a circle on the floor, what path will the ball take when you let go of the string? Many people think it will go straight out, but they are mistaken.

Figure 2–12 is an illustration showing what happens. The ball will travel in a straight line in the direction in which it was going when it was released. This is not surprising, for Newton's first law says that when there is no unbalanced force a body will travel with uniform speed in a straight line. All three of Newton's laws are illustrated by the whirling ball.

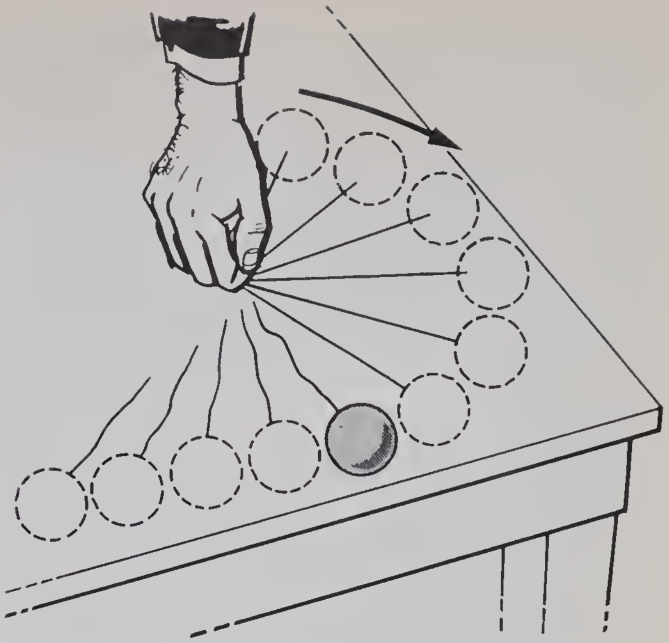


Figure 2–12 A heavy ball which was being whirled on a horizontal surface by means of a string travels in a straight line when it is suddenly released.

The ball you see in Fig. 2–12 moves in a circular path because the string pulls it. The pull is perpendicular to the velocity of the ball; this pull is called **centripetal force.** Centripetal force is always directed toward the center of rotation. As a result of this force, the velocity changes direction. A change in direction is an acceleration and, as stated on p. 11, its magnitude is v^2r, where r is the radius of the curve. According to Newton's second law, $F = ma$. Therefore

$$\text{centripetal force} = ma = m\frac{v^2}{r} = \frac{Wv^2}{gr} \quad \left(\text{since } m = \frac{W}{g}\right)$$

Due to its inertia, the whirling ball exerts a reaction force outward on the string. You can feel this pull if you are holding the string. The pull is called **centrifugal force.** (Remember that *fu*gitives run away to help you remember that centri*fu*gal force is force away from the center.) Centripetal and centrifugal forces are third-law forces that are always *equal* in magnitude and *opposite* in direction. Therefore the magnitude of the centrifugal force can be calculated from the same equation.

Centripetal and centrifugal forces are not balanced forces, because they act on different objects. In the case of the whirling ball,

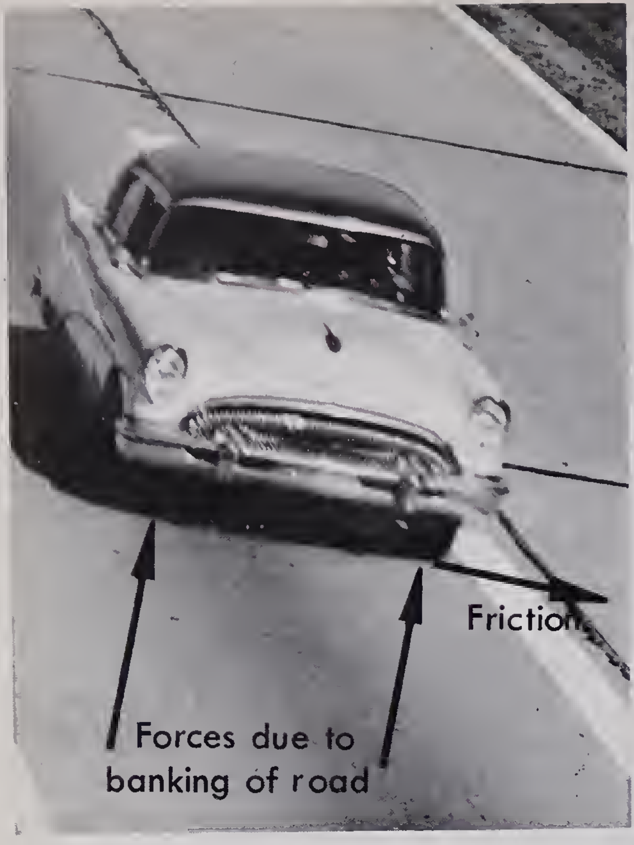


Figure 2–13 The centripetal force that turns this car is supplied by the horizontal components of the forces shown. The vertical components of these forces support the weight of the car.

centrifugal force acts on the string and centripetal force acts on the ball.

For a car to round a curve, a road must exert an inward, centripetal force on the car. This force turns the car. The road can exert this force either because of the friction between tires and road, or by being banked as in Fig. 2–13.

Suppose your car safely rounds a curve at 20 mi/hr. Friction with the road and banking are sufficient to supply the necessary centripetal force. What if you round the curve at 40 mi/hr? Your velocity is twice as great, but since v is squared in the force equation, the force needed is 2^2, or 4 times as great. If you travel at 60 mi/hr, you have a velocity three times as great as 20 mi/hr and therefore need a force that is 3^2 or 9 times as great. If there is not enough friction or if the road is not banked steeply enough, the car will skid at the higher speeds.

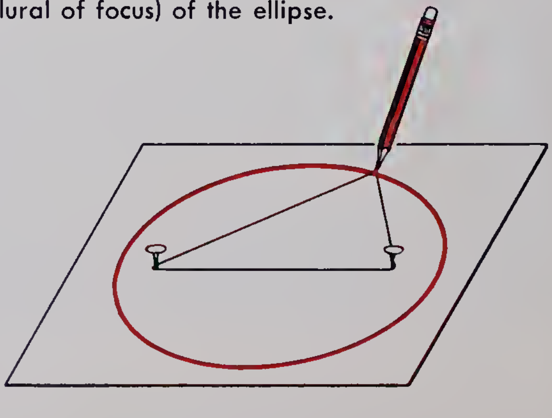
Notice that the radius of the curve is in the denominator of the force equation. The necessary force will be small, at a particular velocity, if r is very large. It is easier to turn in a large curve than in a tight one. If you try to turn a bicycle in a very small circle, you may skid. Here r is very small, so the force needed is very large. You skid when the force of friction between your wheels and the road is less than the force you need to make the turn.

2–25 Objects in space have elliptical paths. If you throw a baseball, it curves along a parabola. If you shoot a gun, the bullet also travels along a parabola, but a larger one. Because the earth itself curves, the direction of the gravitational pull on a long-range missile changes and the path of the missile is not a parabola.

A missile may travel nearly a quarter of the way around the earth before returning to the surface. If the earth were not in the way, the complete path of the missile would be a closed curve. If the speed of the missile increases, it goes farther before returning to earth. Finally, at a speed of about 18,000 mi/hr, the rocket will go into orbit around the earth, becoming an artificial satellite.

Now let the speed increase again. The orbit becomes an ellipse with the center of the earth at one focus. Figure 2–14 shows how an ellipse can be constructed and what is meant by a focus. Satellites with greater and greater speeds travel in longer and

Figure 2–14 An ellipse may be made by using a pencil and a loop of string around two nails as shown. The two nails are at the foci (plural of focus) of the ellipse.



longer ellipses. At a speed of approximately 25,000 mi/hr, the rocket escapes entirely from the earth, never to return.

A rocket that escapes from the earth will have a complicated motion because gravitational forces due to the moon, other planets, and the sun become more important when the rocket is far from the earth. The moon, for example, can change the path of a satellite aimed to go around it, and send the satellite off on an orbit around the sun instead of on the return trip to earth. An error of only a few miles per hour in final speed or a degree in direction can completely change the desired path.

Planets follow elliptical paths in their journeys around the sun. Likewise the moon's path around the earth is an ellipse. The sun is at one focus of the earth's orbit. Nothing is at the other focus.

Self Check

1. You lean up against a wall with a force of 10 lb. What is the reaction force? Give its magnitude, direction, and the object on which it acts.
2. When a bat hits a ball, what are the two forces that act?
3. Why do these two forces not produce equilibrium?
4. Compare the momentum of a bullet with the momentum of the gun from which it has just been fired?
5. What law of physics is illustrated by the bullet and gun?
6. Give two practical applications of this law.
7. A car skids while rounding a curve. Will it skid toward the outside of the curve, toward the inside of the curve, or down the middle of the road?
8. What force turns a railroad train around a curve?
9. Is the gravitational pull of the earth on the sun a centrifugal or a centripetal force?
10. Are centrifugal and centripetal forces larger for a sharp curve or for a wide curve?
11. What effect does doubling the velocity have on centripetal and centrifugal forces?
12. What is the shape of the orbit of a satellite?

Problems

A **1.** If you weigh 120 lb and are running at 10 ft/sec at the moment when you jump onto a sled that has a weight of 10 lb, what will be the velocity of you and the sled? Assume the sled was originally at rest, that it is on level snow, and that there is no friction.

2. Somehow you have become lost in space all by yourself. You have on a space suit with a good supply of oxygen. Altogether you and your suit have a mass of 150 kg. Not counted in this mass is a 2.0-kg tool that you were clutching when you became separated from your space ship. You seem to have zero velocity with respect to the earth, and you would like to get there. You throw your tool in the direction away from earth at a velocity of 10 m/sec. If you are 5000 km away from the earth, how long does it take you to get home? Assume that you threw the tool in the right direction and ignore, for the moment, the gravitational pull of the earth.

3. A 1000-kg car rounds a curve at 20 m/sec. If the curve has a radius of 40 m, what centripetal force must be supplied to keep the car from skidding?

4. When you whirl a weight on a cord in a vertical circle, you find that you do not need to supply a centripetal force when the weight is at the top of its curve. This is because the weight of the object itself supplies the necessary force. How fast would you have to swing a 2.0-kg weight so that it will just make the proper circle if the radius of the circle is 80 cm?

B **5.** A 100-g ball traveling horizontally in a straight groove at 200 cm/sec, strikes a 400-g ball. After the collision, the first ball rebounds at 120 cm/sec, while the other is sent forward. Calculate the velocity of the second ball.

6. A projectile will orbit the earth in a circular orbit if it is fired horizontally with a velocity such that its weight is exactly equal to the centripetal force necessary for an orbit of that radius. Assume that a projectile has been fired horizontally at a height sufficient to avoid its running into mountains. Calculate the necessary velocity in mi/sec. Radius of the earth is approximately 4000 mi. Take g as 32 ft/sec^2. Ignore air friction.

Discussion Questions

1. A fireman holding a heavy hose from which water is spurting leans forward in order to keep his balance. Explain.
2. Does a rocket travel by pushing against the air?
3. In a space station circling the earth at a great distance, you would feel weightless because the ship would be coasting in space (see Fig. 2–6e). Rotation of the station, however, can give you the feeling that you have weight. Why?

Chapter Summary

When a force is exerted on an object, it either deforms the object or causes acceleration, or does both.

Newton's three laws of motion describe the relationship between force and motion. If no unbalanced force acts on an object, its velocity remains constant. The tendency of an object at rest to remain at rest and of an object in motion to continue in motion with constant velocity is called inertia. The mass of an object is a measure of its inertia.

When an unbalanced force acts upon an object it produces an acceleration in the direction of the force that is proportional to the force and inversely proportional to the mass of the object. This law, the second, can also be expressed in terms of momentum, the mass of an object times its velocity. The second law defines the force units, newton (mks), and dyne (cgs), and the mass unit, slug (British engineering).

According to the third law, for every force there is an equal and opposite force. From this law it can be shown that momentum is conserved when objects collide or cause each other to change velocity.

Every mass in the universe attracts every other mass with a force that is directly proportional to the product of the masses and inversely proportional to the square of the distance between them. The weight of an object is the gravitational force between the object and the earth or other large body. Weight is a variable quantity while mass is ordinarily not variable. The kilogram is a mass unit in the mks system, but can also be used as a force unit (kgf).

When an object moves in a curved path, it is accelerated toward the center of the curve by centripetal force. Centrifugal force is the outward force exerted by the moving object on some other object. Satellites move in elliptical orbits.

Vocabulary

force (*p. 27*)
operational definition (*p. 27*)
balanced force (*p. 28*)
unbalanced force (*p. 28*)
first law of motion (*p. 29*)
scientific law (*p. 29*)
inertia (*p. 30*)
mass (*p. 31*)
kilogram of mass (*p. 31*)
gram (*pp. 32, 42*)
second law of motion (*p. 33*)
fundamental units (*p. 33*)
derived units (*p. 33*)
newton (*pp. 33, 42*)
momentum (*p. 34*)
force of gravity (*p. 37*)
constant of gravitation (*p. 39*)
law of universal gravitation (*p. 39*)
weight (*p. 40*)
kilogram of force (*p. 41*)
pound (*p. 41*)
inertial mass (*p. 42*)
gravitational mass (*p. 42*)
dyne (*p. 42*)
slug (*p. 43*)
third law of motion (*p. 45*)
law of conservation of momentum (*p. 47*)
centripetal force (*p. 49*)
centrifugal force (*p. 49*)
ellipse (*p. 50*)

Problems

A **1.** A car with a mass of 1200 kg is traveling in a straight line at a speed of 30 m/sec. It is brought to a stop in 20 sec. Find: (a) Its momentum at the beginning; (b) Its change in momentum; (c) The force necessary to produce this change in momentum; (d) Its acceleration; (e) The force necessary to produce this acceleration.

2. A single pulley wheel is suspended from the ceiling. A rope over the pulley has a mass of 100 kg on one end and a mass of 200 kg on the other. Find the acceleration of the masses. (Hint: Find the unbalanced force and notice how big a mass is being accelerated.)

3. A 6.0 g bullet traveling at 300 m/sec goes through a block of wood in 0.00040 sec and emerges at 100 m/sec. With what force did the wood retard its motion? Solve using both change in momentum and acceleration.

4. An unbalanced force of 1000 N causes a mass to accelerate at 40 m/sec. How great is the mass?

5. ✓ Mars has a diameter 0.54 times that of the earth and a mass 0.11 times that of the earth. If you weigh 100 lb on earth, what would you weigh on Mars?

6. If you weigh 125 lb, what is your weight in newtons?

7. ✓ A 2000-kg rocket accelerates upward at 20 m/sec^2. What total upward force is necessary to give it this acceleration? Express answer in newtons and kgf.

8. If you weigh 150 lb and are running 10 ft/sec at the moment you jump onto a sled which has a weight of 10 lb and which is already moving in the same direction at 5.0 ft/sec, what will be the velocity of you and the sled? Assume that the sled is moving on level snow and that there is no friction.

B **9.** An electron has a mass of 9.1×10^{-28} g. It moves in a radio tube a distance of 4 mm while experiencing a force of 8×10^{-10} dyn. Find its acceleration and final velocity.

10. What velocity is required to give a projectile a circular orbit 4000 mi above the surface of the earth? The centripetal force must be equal to the weight of the projectile. The radius of the earth is about 4000 mi.

11. Calculate the gravitational force of attraction between two 60,000-ton carriers separated by a 300-foot dock.

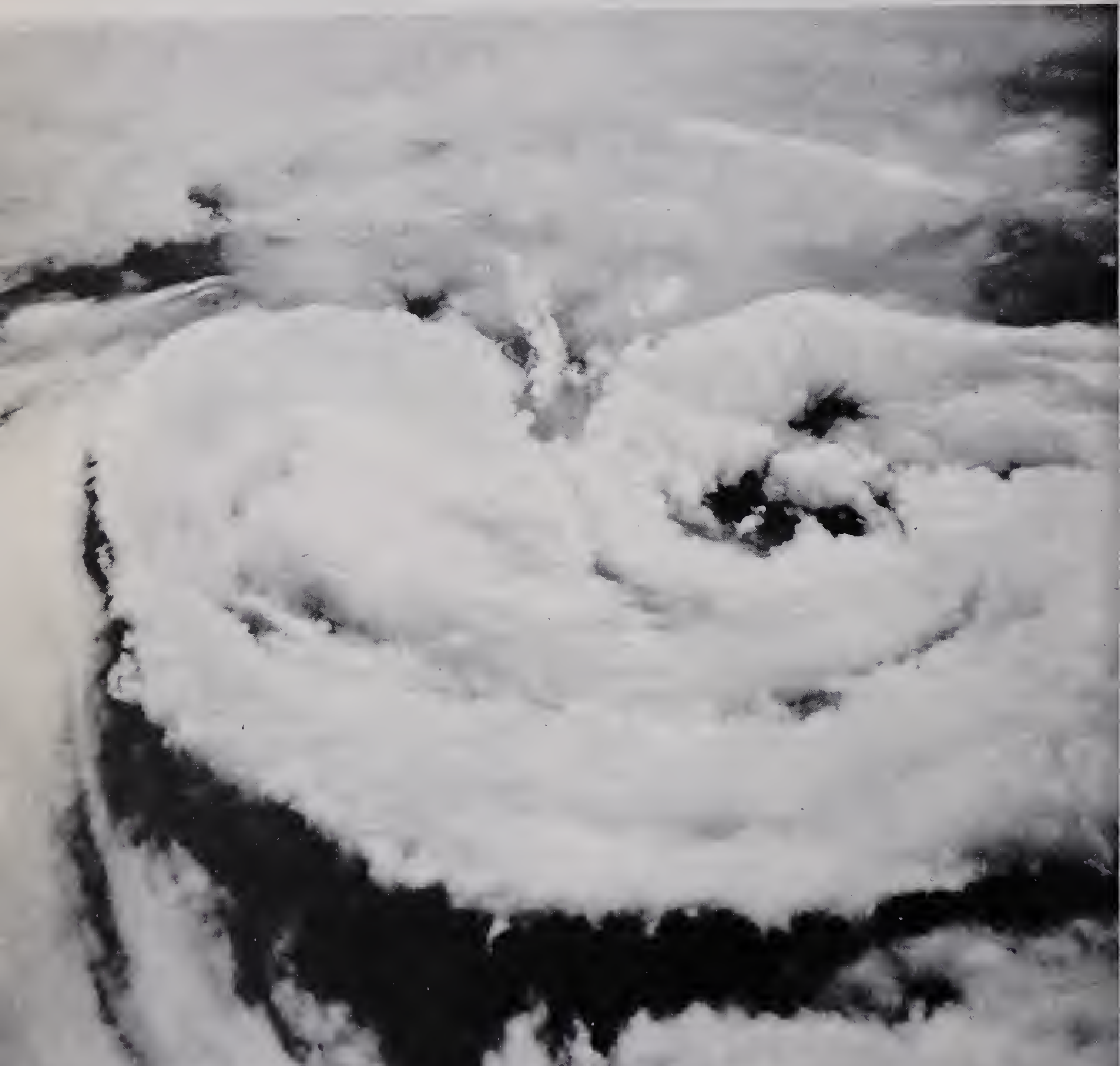
Discussion Questions

1. A bomber has just dropped an atom bomb. should the pilot keep on course or reverse course to avoid being hurt in the explosion?
2. An athlete discovers that he can do a higher high jump in the southern United States than he can in northern Canada. Account for this.
3. Compare the force your feet exert on the floor when you stand with the force the floor exerts on you.
4. You are in the middle of a pond of frictionless ice and would like to get off. How can you do this?

Work on Your Own

1. When you are in a car with your eyes closed, see if you can tell whether the car is turning to the right or left and whether it is speeding up or slowing down because of the direction in which your inertia takes you.
2. Gyroscopes involve special applications of the principle of inerta. You can learn a great deal about gyroscopes by playing with the small toy ones. Consult periodical indexes for references on inertial guidance.
3. Study and explain the operation of a rotating lawn sprinkler.

CHAPTER 3



U. S. Navy Photograph, courtesy of American Meteorological Society, *Weatherwise Magazine.*

The eye of a hurricane, as seen from an airplane above the clouds.

Work and Energy

When you think of energy in large quantities, you may think of the hydrogen bomb. However, even the huge energy of a bomb is small compared to the energy of the sun, the energy of a tropical hurricane, or the energy of ocean tides. In one day Alberta receives as much energy from the sun as is provided by almost one hundred H-bombs.

The energy of a hurricane or of the tides involves motion. What about the energy of the sun? You certainly do not feel motion when the sunshine warms your skin or illuminates the landscape. Yet it is the warmth from the sun that sets in motion the winds in a hurricane (see opposite page). It is obvious that energy can appear in more than one form.

Much of the history of civilization can be written in terms of increasing control and use of energy. Man uses energy to do work. In this chapter you will learn what the physicist means by work, and also how the concept of work helps to make clear the nature of energy.

What Is Work?

3–1 Work is done when a force acts through a distance. A moving hammer can drive a nail. A moving stream of air can blow leaves from a tree. A moving car can knock down a fence. The hammer, the air, and the car all have energy of motion, one type of mechanical energy.

When a hammer is used to drive a nail, the hammer is doing work, and the nail has work done upon it. When the wind blows leaves, the wind does work, and the leaves have work done upon them. The car does work when it knocks down the fence, and the fence has work done upon it.

You can see that the word *work* is being used in a special sense here. Work has a technical meaning as well as the common meanings of exertion, a job, and the like. In each of these examples, a force has been exerted and has produced motion. The physicist says that **work** is done when a force acts through a distance.

3–2 Work is the product of force and distance. Suppose that you pick up a book which has fallen to the floor. You exert a force on the book sufficient to overcome the force of gravity. If the book has a mass of 1.0 kg, the weight is equal to 9.8 N ($W = mg$, see p. 41). You exert a force of 9.8 N in the direction in which the book is moving, that is, upwards. While the book is moving, you are doing work on it. If you lift it a total distance of 1.0 m, you have done 9.8 newton · meters (N · m) of work on the book (Fig. 3–1).

Whenever a force moves an object in the direction in which the force is acting, then the work done on the object is the product of the force and the distance the object moves while the force is acting.

work = force × distance
work = Fs

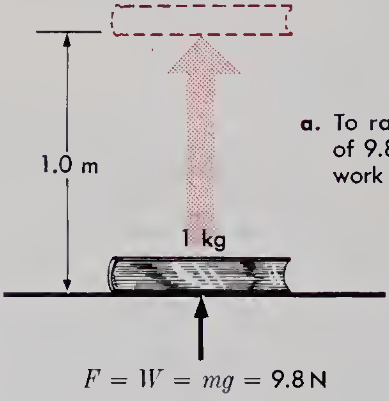
In the first illustration of Fig. 3–1, the boy lifted the 1-kg mass vertically upward by exerting a force that was also directed vertically upward. The force and the distance were in the same direction.

In the second illustration of Fig. 3–1, a box was moved horizontally a distance of 10 m by a horizontal force of 20 N. Here, too, the force and distance were in the same direction. In both of these cases, the work done is found by multiplying the force by the distance.

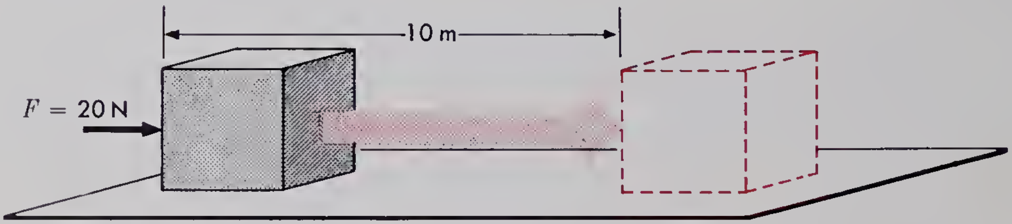
If there had been no friction in the second case, only a small force ($F = ma$) would have been needed to start the box; and the box would have continued to travel across the room even if the force had been removed. The work done in this case would be found by multiplying the force by the distance the box moved while the force was acting, not by the distance across the room. No work would be done while it was coasting.

The weight-lifting situation in Fig. 3–2 presents a somewhat different problem. Here the load of 6.0 kg is lifted from point A to point B. Point B is 1.0 m higher than point A and also 1.5 m to the right. But the force involved in the problem is the force necessary to lift the weight. ($W = mg = 6.0\ \text{kg} \times 9.8\ \text{m/sec}^2 = 59\ \text{N}$).

Figure 3–1



a. To raise a 1.0-kg book requires a force of 9.8 N. If the book is raised 1.0 m, the work done is 9.8 N·m.



b. Because of friction with the floor, a force of 20 N is required to push this box along the floor at uniform velocity. If it is pushed 10 m, the work done is 20 N × 10 m = 2.0 × 10^2 N·m.

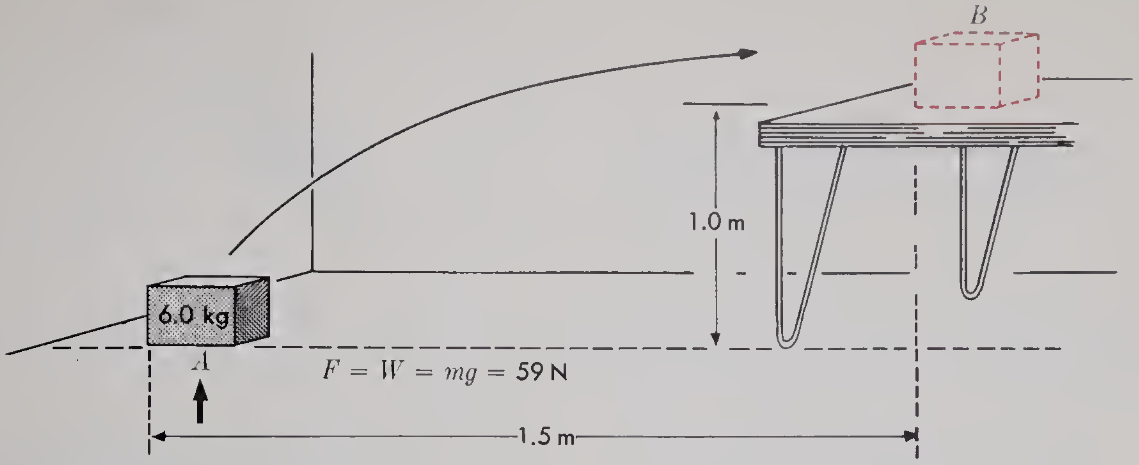


Figure 3–2 The force of gravity on the weight above is vertically downward. Therefore, the only work accomplished is that by the vertically upward force of 59 N through a distance of 1.0 m.

Since weight is a force vertically down, the lifting force must be vertically upward. If work is done only when an object moves in the direction in which the force is acting, then the only distance involved in the doing of work is the vertical one. Therefore, the work done is 59 N times 1.0 m, or 59 N · m. The horizontal distance of 1.5 m has nothing to do with the problem.

3–3 Various units of work are used. In Sec. 3–2, the force is expressed in newtons and the distance in meters. Hence the product is in a derived unit, the *newton · meter.* This unit has a special name, joule (J). (The joule was named for James P. Joule, an English physicist who pronounced his name "jowl." But most people call the unit "jool.") One **joule** is the work done when a force of 1 N acts through a distance of 1 m. Since a newton is a kg · m/sec², 1 joule = 1 kg · m/sec² × m = 1 kg · m²/sec².

In the cgs system of units, the unit of force is the dyne (see p. 42). The unit of work is the dyne · centimeter, which has the special name of **erg.** 1 joule is equal to 10^7 ergs.

In British engineering units, the unit of force is the pound and the unit of work is the **foot · pound** (**ft · lb**). A foot · pound is the work done when a force of 1 lb acts through a distance of 1 ft.

Although force is a vector quantity, and so is the distance, work is a scalar quantity, since it has no particular direction. See Example 1 below.

EXAMPLE 1

How much work is required for a 130-lb boy to climb a ladder 20 ft high? (Notice in this example that the boy does the work on *himself.* Since the work is done on the boy, the force involved is a force sufficient to overcome his weight, that is, a force equal to his weight.)

Given: $F = W = 130$ lb $\quad s = 20$ ft

To find: work

Solution:
$$\begin{aligned} \text{work} &= Fs \\ &= 130 \text{ lb} \times 20 \text{ ft} \\ &= 2.6 \times 10^3 \text{ ft·lb, Answer} \end{aligned}$$

3–4 A force may be resolved into components. It often happens that work is done on an object when the force and dis-

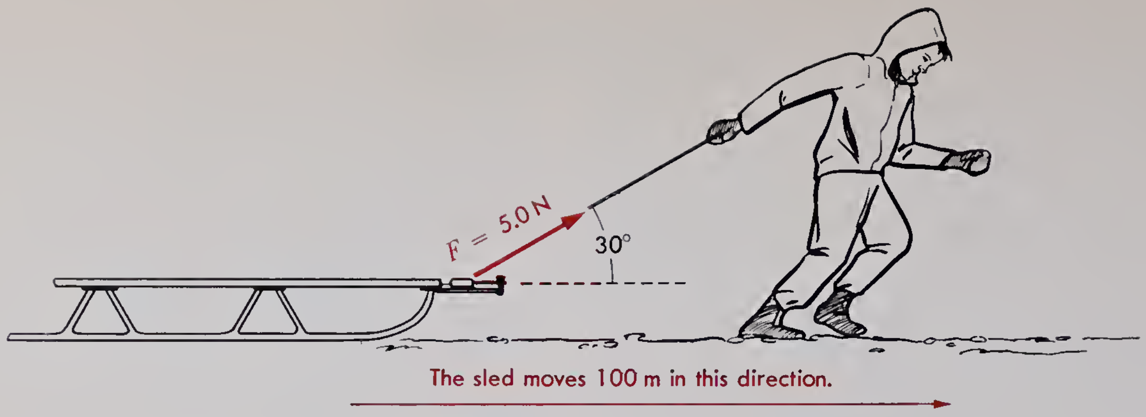

F = 5.0 N
30°
The sled moves 100 m in this direction.

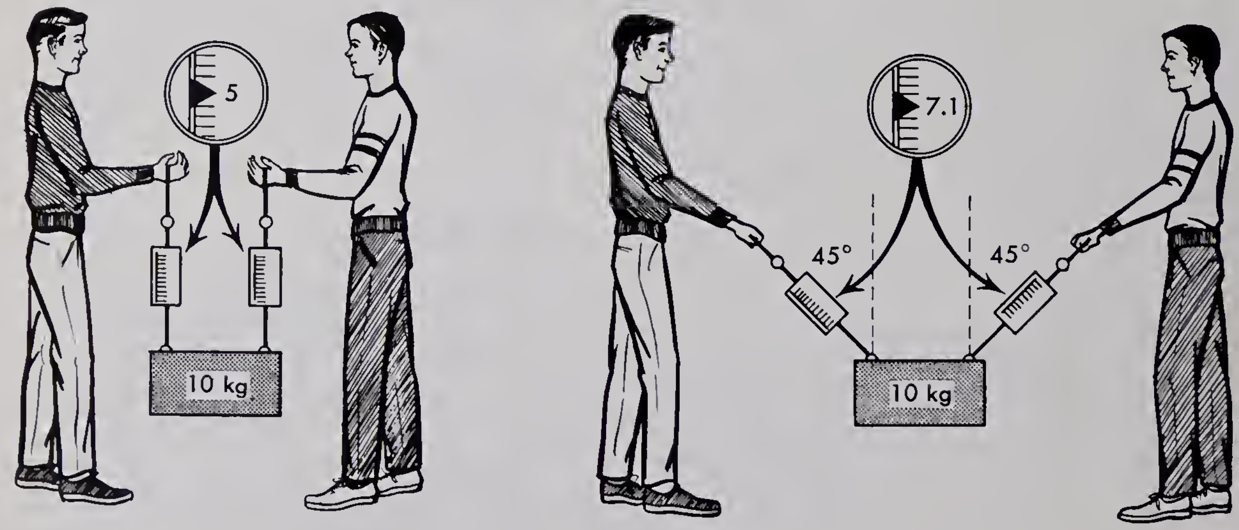
Figure 3–3 The force of 5.0 N here is not in the direction in which the sled moves. Therefore the work cannot be 5.0 N times the distance the sled moves.

tance are not in the same direction. The boy in Fig. 3–3, for example, is pulling a sled along a horizontal piece of ground. The sled rope makes an angle of 30° with the horizontal. Along the rope he is exerting a force of 5.0 N. If he moves the sled 100 m, how much work does he do?

Before this question can be answered, consider the experiment illustrated in Fig. 3–4. In the first case, when the boys pull straight up on the 10-kg block, each one supplies a force of 49 N, a total of 98 N. If they raise the block 1.0 m, they have done 98 N × 1.0 m = 98 J of work. Now suppose they raise the block by pulling at an angle, as in the second case. Each one must now exert a force of 69 N. Does this mean that they do more work than they did in the first case?

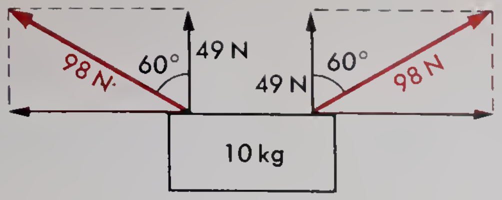
To answer this question, think of it in terms of the work done *on the block* rather than the work done by the boys. A 10-kg block is raised 1.0 m in the first case. The same 10-kg block is raised 1.0 m in the second case. The end result is exactly the same. Therefore, from the point of view of the results of their actions, the work done on the block is exactly the same both times: 98 J. The boys may find that their muscles feel more strain when they pull at an angle, but the work they do is exactly the same in both cases. In the third case, where they

Figure 3–4 Although the force exerted keeps increasing as the boys pull at larger angles, the work they do when they lift the block 1.0 m is still the same.

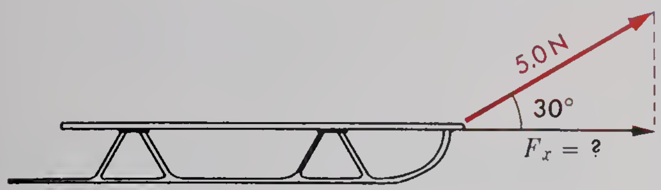


a. When the two boys lift the black by holding their balances vertically, each balance reads 5.0 kg (49 N).

b. When they raise the block by pulling at an angle of 45°, each balance reads 7.1 kg (69 N).



a. Even though the boys in the third case of Fig. 3–4 are pulling with forces of 98 N apiece, the effective upward force is only 49 N, as shown here. The 49 N force is the vertical component of the 98 N force. The horizontal components are equal and opposite and produce no motion.

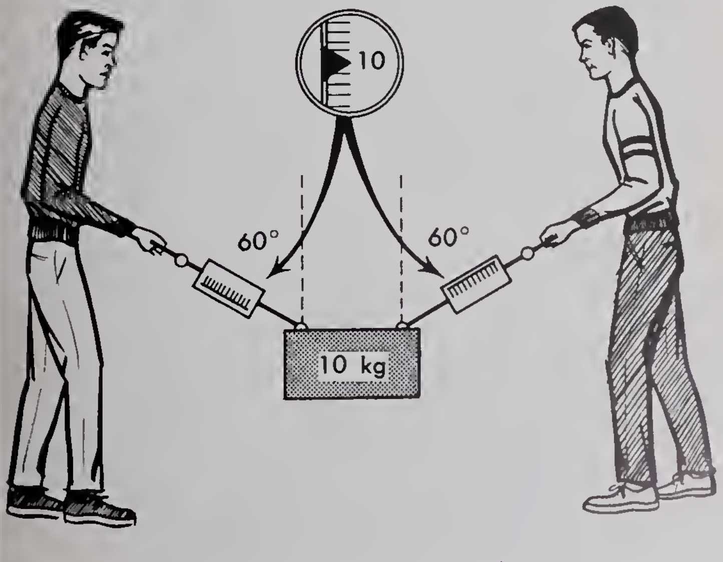


b. The boy with the sled in Fig. 3–3 pulls with a force of 5.0 N. The horizontal component of the force is the effective force doing the work. If you make a scale drawing, you find that $F_x = 4.3$ N. You can also find the value of F_x by trigonometry, as explained in the text.

Figure 3–5 When the applied force is not in the direction of motion, then a component of the force must be used to compute the work.

pull at a greater angle, the final amount of work done is still 98 J, although the boys undoubtedly find it harder to do.

The reason for what seems to be a contradiction here is this: by exerting a force greater than 49 N apiece, as the boys do in the second and third situations, they are doing two things. First, they are lifting the block. But they are also engaged in a mild tug of war, each boy pulling against the other. The force with which each boy pulls against the other is doing no work, because it is causing no motion. Only the upward part, or component, of the force is doing any work. A **component** may be defined as the effective value of a force in a particular direction. In this case, the upward component of each boy's pull must be a force of 49 N, because 98 N are required to raise the block.



c. When they raise the block by pulling at an angle of 60°, each balance reads 10 kg (98 N).

How a component is related to a force is illustrated in Fig. 3–5. Here is the same example as the third case of Fig. 3–4. The 98 N exerted by each boy is represented as the hypotenuse of a right triangle, and the vertical side of the triangle is the desired component of the force. The horizontal side of the triangle is the tug-of-war component. The second drawing of Fig. 3–5 shows how to find the work done by the boy with the sled in Fig. 3–3. By making a scale drawing, with the 5.0 N force and the 30° angle, you can easily find out that the horizontal component is 4.3 N. If the sled is moved 100 m, then the work done is 4.3×10^2 N · m, or 4.3×10^2 J.

A better definition of work than the one given earlier would be that work is equal to force times distance, where the force is either in the same direction as the distance or is a component in that direction.

Do It Now

Try the experiment illustrated in Fig. 3–4. Does the force go up regularly as you increase the angle, or does it increase more rapidly for some angle changes than for others? What do you think the force would be if you pulled at an angle of 90°?

3–5 Components can be determined by trigonometry. The simplest way to find a component is by trigonometry. You should not try to read this section unless you know how to use trigonometric functions.

Look again at the sled problem diagramed in Fig. 3–5. For the right triangle shown, you can set up the following equation:

$$\frac{F_x}{5.0\ \text{N}} = \cos 30^\circ$$

Solving for F_x:

$$\begin{aligned} F_x &= 5.0\ \text{N} \times \cos 30^\circ \\ &= 5.0\ \text{N} \times 0.866 \\ &= 4.3\ \text{N} \end{aligned}$$

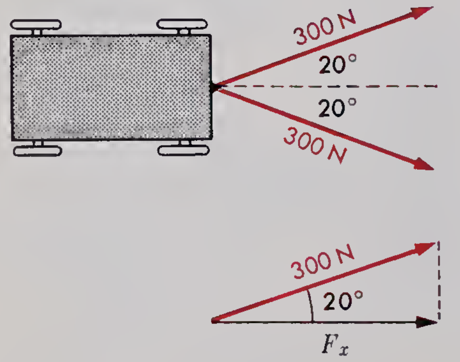


Figure 3–6 A cart is being pulled by 2 men dragging on ropes attached as shown. If each one pulls with a force of 300 N, the force component in the direction of the motion can be calculated by trigonometry, using the force triangle of the second diagram.

Take another case (Fig. 3–6). Two men are dragging a load by pulling on ropes. If they pull the load a distance of 100 m, how much work do they do? Often in solving a problem of this sort, it is a good idea to make a separate picture of the force vectors. This is done in the second drawing. In this right triangle:

$$\frac{F_x}{300\ \text{N}} = \cos 20^\circ$$

$$\begin{aligned} F_x &= 300\ \text{N} \times \cos 20^\circ \\ &= 300\ \text{N} \times 0.940 \\ &= 282\ \text{N} \end{aligned}$$

Since there are two men pulling, the total force is 2 × 282 N or 564 N. Therefore:

$$\begin{aligned} \text{work} &= Fs \\ &= 564\ \text{N} \times 100\ \text{m} = 5.64 \times 10^4\ \text{J} \end{aligned}$$

Notice in both of these problems that the force component doing the work is equal to $F \cos \theta$, where F is the applied force and θ is the angle between the applied force and the direction of motion. Therefore

$$\text{work} = Fs \cos \theta$$

This equation is true for all situations. When F and s are in the same direction, θ is 0 and $\cos \theta$ is 1.

3–6 Force alone does not do work. A strong man in the circus is doing work when he lifts a very heavy weight from the floor to a position above his head. However, when he stands there holding it, he does no work, even though he may be getting tired. The work done is zero because the distance through which the force is exerted is zero, unless he should lift it higher. Even when he walks around the room carrying the weight, he still does no work, because the force is vertical and the distance horizontal. There is no component of the force in the direction of the distance. Or, from the point of view of trigonometry, θ is 90°; for this angle, $\cos \theta$ is zero.

Self Check

1. What is a joule?
2. What is a component of a force?
3. How much work is done if (a) a horizontal force of 5.0 N is used to push a box 2.0 m along a level floor; (b) a 2.00-kg rock is lifted 1.00 m; (c) a 2.00-kg rock held in the hand is moved horizontally 1.00 m?
4. A 100-lb boy climbs a flight of stairs. The distance along the stairs is 15 ft, while the vertical height of the stairs is 10 ft. How much work must the boy do to lift himself?

Problems

Ⓐ **1.** How much work is done if a 20.0-kg trunk is lifted a height of 10.0 m?

2. A horizontal force of 25.0 N is required to push a table across a room. How much work is done in pushing the table 4.00 m?

3. A steel beam weighing 2 tons is lifted 100 ft into place. How much work is done on the beam?

4. A mother cat decides to move her litter to a new location. She has six kittens, each weighing 125 g. She moves them 8.0 m across the barn floor and up onto a box 50 cm high. How much work did she do?

5. A woman pushes on the handle of a floor waxer with a force of 10 lb. If the handle makes an angle of 50° with the floor, how much work does she do when she pushes the waxer 20 ft?

6. A boy coasting downhill in a wagon brings it to a halt in 10 m by pushing his feet on the ground. If his legs make an angle of 40° with the ground and each leg applies a force of 30 N down the axis of the leg, how much work does he do?

7. A boy pulls a sled along level ground for a distance of 200 ft by exerting a force of 8.0 lb at an angle of 35° with the horizontal. How much work does he do on the sled?

Ⓑ **8.** Prove that 1 J equals 10^7 ergs.

Discussion Questions

1. When you hit a baseball with a bat, is work done on the ball?
2. If you support a beam while someone is nailing it into place, are you doing work? Is the person who nails the beam doing work?

What Is Power?

3–7 Power is work done per unit of time. Suppose that a truck, illustrated in Fig. 3-7, carries a 2.0-T load of bricks to the top of a loading ramp 8.0 ft high. The useful work performed is:

$$\text{work} = Fs = 4.0 \times 10^3 \text{ lb} \times 8.0 \text{ ft}$$
$$= 3.2 \times 10^4 \text{ ft·lb}$$

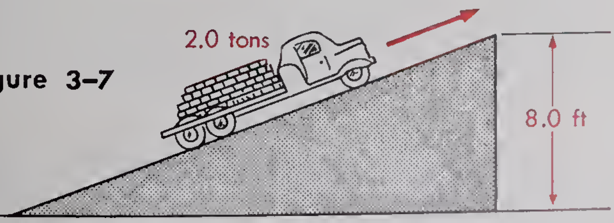


Figure 3–7

A worker carrying 50 lb per load could do the same work in 80 loads. Even though the work done is the same in both instances, there is a big difference in the time required. Thus the truck might do the job in 15 sec, while the workman might require an hour. The truck and the man work at different rates.

In physics the rate of doing work is called **power** (P). In the language of mathematics,

$$P = \frac{\text{work}}{\text{time}} = \frac{Fs}{t}$$

To find the *useful* power developed by the workman:

$$P = \frac{Fs}{t} = \frac{4.0 \times 10^3\ \text{lb} \times 8.0\ \text{ft}}{60\ \text{min}}$$
$$= 5.3 \times 10^2\ \text{ft·lb/min}$$

Of course, the laborer's muscles develop more power than this solution indicates, but most of it was consumed in carrying his own body up and down the ramp and in overcoming internal friction in the body.

The truck, doing the same amount of work, does it faster. What is its useful power?

$$P = \frac{Fs}{t} = \frac{4.0 \times 10^3\ \text{lb} \times 8.0\ \text{ft}}{1/4.0\ \text{min}}$$
$$= 1.3 \times 10^5\ \text{ft·lb/min}$$

3–8 Power may be expressed in horsepower or watts.

Power can be expressed in foot pounds per minute, but in English units it is usually expressed in horsepower. This unit was first defined in the latter part of the eighteenth century by James Watt as he tried to compare the power of his steam engine with the power of a horse. He had some work-horses walk round and round a wheel used to raise a 100-lb weight out of a deep well. He found that a horse could walk for an extended period of time at a rate of about 2.5 mi/hr while lifting the weight. This represents a distance of 2.5 × 5280 ft in 60 min. The power therefore was:

$$P = \frac{2.5 \times 5280\ \text{ft} \times 100\ \text{lb}}{60\ \text{min}}$$
$$= 22{,}000\ \text{ft·lb/min}$$

However, he knew his wheel developed much friction, so he estimated that the horse was actually exerting about 150 lb to lift the load. In that case the power of the horse was about 33,000 ft · lb/min; this value became the definition of **horsepower** (**hp**).

In metric units, the unit of power is the **watt** (**W**), which is 1 J/sec, or 1 N · m/sec. You are probably familiar with the use of watts in electricity. Fundamentally the watt is a unit of mechanical power. A 40-watt electric light bulb consumes the electrical power that could be obtained by converting 40 J of mechanical work into electrical energy each second. The **kilowatt** (**kW**) is 1000 watts.

3–9 The kilowatt hour is a unit of work.

Since the watt is a unit of power, people often think that the kilowatt · hour is also a unit of power. It is not. It is a unit of work. To see why this is so, go back to the meaning of the watt:

$$1\ \text{watt} = 1\ \frac{\text{J}}{\text{sec}}$$

Treat this like an equation and multiply both sides by 1 sec:

$$1\ \text{watt·sec} = 1\ \text{J}$$

The watt · sec is therefore a unit of work or energy equal to a joule. It is the amount of work done in 1 sec by a machine or other power source working at the rate of 1 watt.

Now consider the kilowatt:

$$1\ \text{kilowatt} = 1000\ \text{watts} = 1000\ \frac{\text{J}}{\text{sec}}$$

Multiply both sides by 1 hr:

$$1\ \text{kilowatt·hour} = 1000\ \frac{\text{J}}{\text{sec}} \times 1\ \text{hr}$$
$$= 1000\ \frac{\text{J}}{\text{sec}} \times 3600\ \text{sec}$$
$$= 3{,}600{,}000\ \text{J}$$
$$= 3.6 \times 10^6\ \text{J exactly}$$

The **kilowatt · hour** (**kWh**) is therefore also a unit of work. It is the work done in 1 hr at the rate of 1 kW. A 100-watt light bulb that operates for 5 hr consumes 5 × 10² watt · hr of work, or 0.5 kWh.

3–10 Jet engines are rated in terms of thrust.

When an aeronautical engineer speaks of the performance of a jet engine, he usually speaks of its *thrust*. This is sometimes confusing to those who are used to rating engines in terms of horsepower. Actually, **thrust** is the force exerted on the plane by the exhaust gases. The power formula can be rearranged thus:

$$P = \frac{\text{work}}{\text{time}} = \frac{Fs}{t} = F \times \frac{s}{t} = Fv$$

From this, you see that power is the product of force, or thrust, times velocity. Of course, this relationship holds for cars, ships, or even sprinters, as well as for jets, but it is particularly useful with rockets and jet aircraft. The power such engines can deliver varies widely with their velocities. Study Example 2 below.

EXAMPLE 2

A fighter plane uses a single jet engine with a thrust of 10,000 lb. What horsepower does it deliver when flying at 600 mi/hr?

Given: $F = 10{,}000 \text{ lb}$

$$v = 600 \text{ mi/hr} = \frac{600 \times 5280 \text{ ft}}{60 \text{ min}}$$

$$= 5.28 \times 10^4 \text{ ft/min}$$

To find: P in hp

Solution: $P = Fv$

$$P = 10{,}000 \text{ lb} \times 5.28 \times 10^4 \text{ ft/min}$$

$$= \frac{10{,}000 \times 5.28 \times 10^4}{33{,}000} \text{ hp}$$

$$= 1.60 \times 10^4 \text{ hp, Answer}$$

Self Check

1. Which of the following are units of power? ft · lb; hp; J; kWh; mi · ton/sec; watt.
2. A 1.0-kg book is raised from the floor to a table 1.0 m high in 2.0 sec. What is the power developed?
3. How much work will a 2.0-hp motor do in 1.0 min?
4. Define power.
5. A machine does 90 J of work in 1.0 min. What power does it deliver?
6. A boy uses a force of 10 N to move a crank handle at the rate of 2.0 m/sec. What is his power?
7. Convert 3 kW to J/sec.

Problems

A

1. A 100-g mouse runs up a flight of stairs in 10 sec. If the two floors are 4.0 m apart, what is the power developed by the mouse?

2. A 120-lb boy runs up a flight of stairs in 10.0 sec. If the two floors are 12.0 ft apart, what is the power developed by the boy? Express in ft · lb/sec, ft · lb/min, and horsepower.

3. What is the power of a crane that lifts 20 1000-kg steel girders to a height of 30 m in 2.0 min? Express in W and kW.

4. A customer is billed for 120 kWh of electricity. How many joules did he use?

5. What is the power delivered by a locomotive if it exerts a pull of 9.00 tons while pulling a train at 60.0 mi/hr? Express the answer in horsepower.

6. Express 1 hp in ft · lb/sec.

7. A moving belt carries boxes of apples up an incline to load them on a truck. The boxes weigh 15 kgf and they are loaded at the rate of 10 per min. If the incline is 5.0 m long, with the upper end 120 cm higher than the other, what is the useful power delivered by the belt?

8. The average annual consumption of electricity by a household in Calgary, Alberta, is about 4,200 kwh. A medium-weight car has a mass of about 1000kg. The height of Mt. Everest is 8850 m. How many medium-weight cars could be raised to this height by the expenditure of 2,500kwh?

B

9. Convert 1 hp to watts, and use the result to determine the power output in watts of a ¼-hp motor.

10. A boy turns a crank at the rate of 120 turns per minute by applying a steady force of 5.0 lb to the handle. The distance from the axle to the handle is 1.0 ft. Find his horsepower.

What Is Energy?

3–11 Energy is the ability to do work. What does a physicist mean when he talks about energy? Much of the time he is thinking about objects in motion. Air in motion, as in a hurricane, has a great deal of energy. It can pick up heavy objects and carry them great distances. Water in motion in a stream has energy, energy that can wash away soil or turn the wheels that operate an electric generator. Notice that one of the characteristics of energy is that it can be used to do work. The stream of water exerts a force on a generator wheel. The force acts through a distance, as the wheel turns, and work is done on the wheel. **Energy** is often defined as the ability to do work.

Another useful characteristic of energy is that it can be passed from one object to another. The water that turns the generator wheel loses energy and is slowed down. The generator wheel is set into motion; it gains energy.

3–12 Energy may be either kinetic or potential. The energy that a moving object possesses because of its motion — the energy of the moving water of the stream, for example — is called **kinetic energy** (E_k).

Sometimes energy is not being expended, but has the potentiality of being able to do work when released. This stored energy is called **potential energy** (E_p) and may result from an object's position or condition.

An example of potential energy of position is the energy of water in a dammed-up stream. The water is not moving; it has no kinetic energy, but it does have the potentiality of moving and of doing work and thus has potential energy.

A stretched rubber band has potential energy of condition. If the band is part of a slingshot and you release the band, the energy is passed to the pebble, which then has kinetic energy.

3–13 One form of energy may be converted to another. The energy of motion — whether that energy is in action or stored — is called **mechanical energy**. Water running downhill in the stream has kinetic mechanical energy. The water in a cloud may not be moving, but it has the potentiality of motion. It has potential mechanical energy. As the rain falls, this potential energy is changed to kinetic mechanical energy.

Heat, too, is a form of energy. Radiation from the sun heats the surface of the earth, causing the evaporation of water from the ocean and other bodies of water. Heat is the energy that does the work of raising the water, most of which forms clouds.

Some other familiar forms of energy are *electrical energy, sound,* and *light.*

A characteristic of energy is that it can be converted from one form to another. The heat energy that evaporates water from the ocean is converted to mechanical energy of the water in the cloud. The electrical generator turned by running water converts mechanical energy into electrical energy. A light bulb converts electrical energy into heat energy and light energy. A radio converts electrical energy into sound energy. A television set converts electrical energy into sound energy and light energy. Any form of energy can be converted into any other form if the proper devices are used.

The more scientists learn about forms of energy, the more they discover that they are not as different from one another as they may seem at first. It is now known that heat energy and sound energy involve motion of the tiny molecules of which matter is composed, and that electrical energy also involves motion of tiny particles. Light energy originates in the motion of particles within atoms. No matter what phase of energy the physicist studies, he finds that an understanding of mechanical energy is fundamental to an understanding of the other forms.

3–14 Energy can be stored. Energy can be stored in various ways. For example, a green plant uses energy from the sun to build materials which become part of the plant body. Thus green plants store some of the energy radiated by the sun. The storage involves a chemical change; hence the energy stored in plant bodies is **chemical energy**. When wood from trees is burned, the energy stored in the wood is released as heat and light. This too is a chemical change. When you eat plant food, the stored energy in the food is released in your body as heat and mechanical energy. Again the release of energy accompanies a chemical change.

Mechanical energy can also be stored, as you have just learned. Mechanical energy is required to compress a spring or lift a rock. This energy is stored in the spring or rock. When you let go of them, they move as the energy is released.

The energy from a nuclear-power plant comes from the nuclei of atoms. As the reaction proceeds, some of the mass of the nucleus disappears and heat, light, sound, and mechanical energy appear. Apparently *matter* itself is a stored form of energy.

3–15 Energy is always conserved. Does energy get used up as it is converted from form to form? For example, when a stream turns the wheels of a generator, the water loses energy and the generator gains energy. Are the two quantities of energy equal or has some energy disappeared? When the electrical energy produced by the generator is used to operate a motor in a distant factory, is the energy of the motor exactly equal to the electrical energy sent to the factory by the generator or is it less?

These are questions that are not easy to answer because very precise measurements are necessary. In the case of the motor, for instance, electrical energy is being converted not only into mechanical energy, but into heat and sound energy as well.

Many careful measurements made over a period of more than a hundred years indicate that energy is a quantity that does not get used up. Scientists say that it is *conserved*. The **law of conservation of energy** is: Energy can neither be created nor destroyed, but may be converted from one form to another. Note that the same law can be applied to matter since matter can be converted into energy (Sec. 3–14).

When a speeding car hits a brick wall, the car comes to rest and so, eventually, do the bricks of the wall. What has become of the energy of the car? If you were able to investigate the situation completely, you would find that most of the car's mechanical energy had become heat energy, making the metal of the car and the rubber of the tires, the soil of the earth and the stones of the wall just a little hotter than before. Touching a nail that you have been hammering shows you that mechanical energy has been converted to heat energy. In most cases where it appears that energy might have disappeared, you will find that the missing energy has been converted to heat.

Self Check

1. In what way is the energy of a cloud (composed of many drops of water) like the energy of a moving stream of water?
2. In what way is the energy of a cloud different from the energy of a moving stream of water?
3. What energy conversion takes place in an electric clock?

4. Name seven forms of energy and tell which are stored forms.
5. Why is an understanding of mechanical energy fundamental to an understanding of most other forms?
6. Give a definition of energy.
7. What is the law of conservation of energy?

Discussion Questions

1. Trace the energy conversions from a pile of coal to the heat in an electric toaster.
2. Trace the energy conversions from the heat from the sun to the energy of a home-run baseball.
3. If you roll a ball along a level floor it slows down and comes to rest. What has happened to its original energy?
4. What everyday experiences, not described in the text, show that mechanical energy is easily converted to heat?
5. It is sometimes said that the sun is the source of all energy on the earth. Does this apply to the energy obtained from coal? oil? water power? uranium? Explain.
6. Can you think of devices that make the following energy conversions: light to electrical; mechanical to light; sound to electrical; sound to mechanical?

Measuring Energy

Since energy is the ability to do work, the quantity of energy is measured in work units. When work is done on an object, the object gains energy equal to the amount of work done. If the object does work, it loses energy; the amount it loses is equal to the work it has done.

3–16 Potential energy is easily measured. The potential energy of an object is equal to the work done on it to put it into its position or condition. It is also equal to the work the object can do when released from its position or condition.

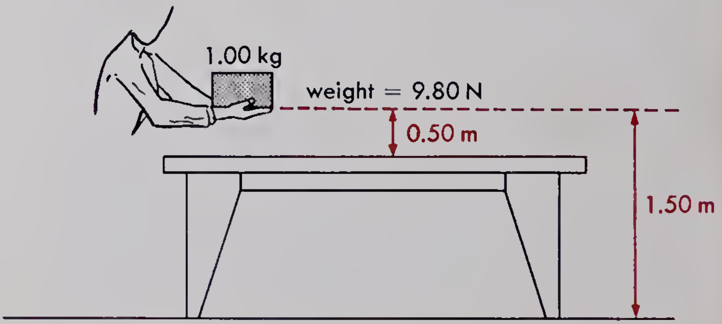
If you lift a weight, the force you exert is equal to its weight. For example, if you lift a 2.00 kg object 1.00 m, the work you do is:

$$\begin{aligned}\text{work} &= Fs\\ &= Wh \text{ (}h\text{ being the height you raise it)}\\ &= mgh \text{ (since } W = mg\text{)}\\ &= 2.00\text{ kg} \times 9.80\text{ m/sec.}^2 \times 1.00\text{ m}\\ &= 19.60\text{ N} \times 1.00\text{ m}\\ &= 19.6\text{ J}\end{aligned}$$

The potential energy of the object is equal to the work done on it to raise it, or 19.6 J. If you drop the weight, it will be able to do 19.6 J of work on the object that it hits.

Potential energy is always measured with respect to some point. For example, in Fig. 3–8, a boy is holding a 1.00-kg block above a table. The block has a potential energy with respect to the table, equal to the work done to lift it 0.50 m.

Figure 3–8 Potential energy must be measured with respect to some point. The potential energy of the block with respect to the table is 4.9 J. Its potential energy with respect to the floor is 14.7 J.



$$
\begin{aligned}
E_p &= mgh \\
&= 1.00\ \text{kg} \times 9.80\ \text{m/sec}^2 \times 0.50\ \text{m} \\
&= 4.9\ \text{J}
\end{aligned}
$$

If the block drops to the table, it can do 4.9 J of work. This will be converted partly to sound energy, but mostly to heat energy, warming both the block and the table.

With respect to the floor, the block of Fig. 3–8 has a potential energy equal to the work done to lift it 1.50 m.

$$
\begin{aligned}
E_p &= mgh \\
&= 1.00\ \text{kg} \times 9.80\ \text{m/sec}^2 \times 1.50\ \text{m} \\
&= 14.7\ \text{J}
\end{aligned}
$$

If the block drops to the floor, it can do 14.7 J of work when it hits.

If you are working with English units in a problem, then you will use $E_p = Wh$, with W expressed in lb. This is illustrated by Example 3 at the right.

EXAMPLE 3

A 2000-lb weight is dropped 10 ft onto the top of a post and drives the post 1.0 ft into the ground. (a) How much energy does the weight deliver to the post? (b) How much work can the weight do? (c) With what average force does it drive the post?

Given: W = 2000 lb; h = 10 ft + 1 ft = 11 ft (because the weight ends up 11 ft lower than its starting point); s (for post) = 1.0 ft

To find: (a) E_p of weight; (b) work done by weight; (c) F on post

Solution: (a)
$$
\begin{aligned}
E_p &= Wh \\
&= 2000\ \text{lb} \times 11\ \text{ft} \\
&= 2.2 \times 10^4\ \text{ft·lb, Answer}
\end{aligned}
$$

(b) 2.2×10^4 ft·lb, Answer

(c) work = Fs

$$2.2 \times 10^4\ \text{ft·lb} = F \times 1.0\ \text{ft}$$

$$
\begin{aligned}
F &= \frac{2.2 \times 10^4\ \text{ft·lb}}{1.0\ \text{ft}} \\
&= 2.2 \times 10^4\ \text{lb, Answer}
\end{aligned}
$$

3–17 Kinetic energy equals work done.

The kinetic energy of an object is equal to the work done to accelerate it from rest. Suppose that you have lifted a 5.0-lb stone a height of 6.0 ft. The potential energy of the stone is:

$$
\begin{aligned}
E_p &= Wh \\
&= 5.0\ \text{lb} \times 6.0\ \text{ft} = 30\ \text{ft·lb}
\end{aligned}
$$

Now drop the stone. It falls, gaining speed as it goes. Obviously, it has kinetic energy, the energy of motion, and the amount of kinetic energy is increasing. The kinetic energy is equal to the work done on the stone as it falls. To calculate this energy you need to know the size of the force acting and the distance. The force, in the direction of the motion, is the weight of the stone. Therefore, if the stone has fallen 2.0 ft, the kinetic energy is:

$$
\begin{aligned}
E_k &= \text{work done to accelerate the falling object} \\
&= \text{weight of the object} \\
&\qquad \times \text{ the distance it has fallen} \\
&= 5.0\ \text{lb} \times 2.0\ \text{ft} = 10\ \text{ft·lb}
\end{aligned}
$$

In the meantime, what has happened to the potential energy of the stone? After it has fallen 2.0 ft, the stone is 4.0 ft from the ground, so its potential energy is:

$$
\begin{aligned}
E_p &= Wh \\
&= 5.0\ \text{lb} \times 4.0\ \text{ft} = 20\ \text{ft·lb}
\end{aligned}
$$

At this point the stone has a kinetic energy of 10 ft · lb and a potential energy of 20 ft · lb, making a total of 30 ft · lb. Notice that this is just exactly the energy it had when it was held in your hand at a height of 6.0 ft. Some of the original potential energy has changed to kinetic energy. No energy has been created; no energy has been destroyed. The energy has been conserved.

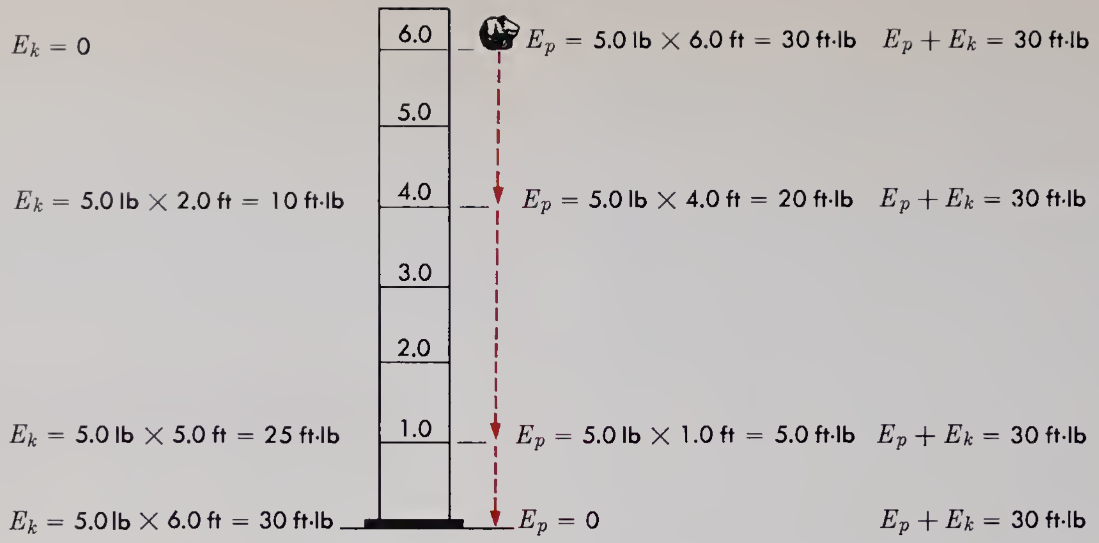

$E_k = 0$
6.0
E_p = 5.0 lb × 6.0 ft = 30 ft·lb
$E_p + E_k$ = 30 ft·lb
5.0
E_k = 5.0 lb × 2.0 ft = 10 ft·lb
4.0
E_p = 5.0 lb × 4.0 ft = 20 ft·lb
$E_p + E_k$ = 30 ft·lb
3.0
2.0
E_k = 5.0 lb × 5.0 ft = 25 ft·lb
1.0
E_p = 5.0 lb × 1.0 ft = 5.0 ft·lb
$E_p + E_k$ = 30 ft·lb
E_k = 5.0 lb × 6.0 ft = 30 ft·lb
$E_p = 0$
$E_p + E_k$ = 30 ft·lb

Figure 3–9 When a 5.0-lb rock is 6.0 feet above the ground, it has 30 ft · lb of potential energy. As it falls, its potential energy decreases and it gains kinetic energy.

Figure 3–9 illustrates this problem and shows the values of kinetic and potential energy at four different levels. In every case, their sum is the same.

3–18 Increasing the velocity increases the kinetic energy. The faster an object moves, the greater is its kinetic energy. This energy is equal to the work that is done to accelerate it from rest to its velocity:

$$E_k = \text{work} = Fs$$

In this case, F is the unbalanced force accelerating the body. According to Newton's second law:

$$F = ma$$

Therefore

$$E_k = mas$$

When an object is accelerated from rest, the distance is given by the equation:

$$s = \tfrac{1}{2}at^2$$

This can be substituted for s in the kinetic energy equation:

$$E_k = ma \times \tfrac{1}{2}at^2 = \tfrac{1}{2}ma^2t^2 = \tfrac{1}{2}m(at)^2$$

But when an object accelerates from rest, its velocity is:

$$v = at$$

Substitute v^2 for $(at)^2$ in the equation for energy:

$$E_k = \tfrac{1}{2}mv^2$$

One interesting fact about this equation is that acceleration is not a factor in it. The energy of a moving body depends on its mass and on its velocity, and is not affected by how quickly it reached that velocity. See Example 4.

EXAMPLE 4

What is the kinetic energy of a 10-kg rocket traveling at 800 m/sec?

Given: m = 10 kg v = 800 m/sec

To find: E_k

Solution: $E_k = \tfrac{1}{2}mv^2$

$$E_k = \tfrac{1}{2} \times 10\text{ kg} \times \frac{(800)^2\text{ m}^2}{\text{sec}^2}$$
$$= 3.2 \times 10^6\text{ kg·m}^2/\text{sec}^2$$
$$= 3.2 \times 10^6\text{ J, Answer}$$

The kinetic energy equation works equally well in British engineering units if you convert pounds of mass to slugs. However, the equation can be written in another form, involving weight only, and then you do not need to use slugs. Since $W = mg$, then $m = W/g$. When this is substituted for m in the kinetic energy equation, you have:

$$E_k = \frac{Wv^2}{2g}$$

Study Examples 5 and 6 below.

EXAMPLE 5

What is the kinetic energy of a 2000-lb car traveling at 60 mi/hr?

Given: $W = 2000\ \text{lb}$
$v = 60\ \text{mi/hr} = 88\ \text{ft/sec}$

To find: E_k

Solution:

$$E_k = \frac{Wv^2}{2g}$$

$$= \frac{2000\ \text{lb} \times (88)^2\ \text{ft}^2/\text{sec}^2}{2 \times 32\ \text{ft/sec}^2}$$

$$= 2.4 \times 10^5\ \text{ft}\cdot\text{lb},\ \text{Answer}$$

EXAMPLE 6

If the car of Example 5 travels 200 ft while being brought to a stop, what average force has acted to slow the car?

Given: $E_k = 2.4 \times 10^5$ ft·lb (from Example 5)
$s = 200\ \text{ft}$

To find: F

Solution: E_k = work done by car while slowing down

$$E_k = Fs$$

$$F = \frac{2.4 \times 10^5\ \text{ft}\cdot\text{lb}}{200\ \text{ft}}$$

$$F = 1.2 \times 10^3\ \text{lb}$$

This is the average force exerted by the car while it is stopping. It is opposed by an equal and opposite stopping force.
Answer

Self Check

1. If you lift a 2-lb weight 3 ft, how much work do you do?
2. As a result of the lifting, what change, if any, has occurred in the energy of the weight?
3. If the weight is then dropped, what is its energy after falling 1 ft?
4. After falling 3 ft, what is its energy while it is still moving?
5. What becomes of the energy when the weight comes to rest?
6. One hundred joules of work are done on a spring to compress it. What is its potential energy?
7. If the spring is used to shoot a projectile, how much energy will it give to the projectile?
8. Will the energy given to the projectile be kinetic or potential?
9. Compare the kinetic energies of two balls that have fallen the same distance, if one of them has twice the mass of the other.
10. Compare the kinetic energies of two balls if their masses are the same, but one has twice the speed of the other.

Problems

A

1. A 10-lb weight is held 3.0 ft above the floor of a room. What is its potential energy with respect (a) to the floor? (b) to the floor of the cellar 10 ft below the floor of the room?

2. A 10.0-kg rock is dropped 20.0 m. (a) How much work can it do? (b) What becomes of the energy after it hits?

3. A spring is compressed 10 cm by the application of an average force of 50 N. (a) What is the potential energy of the spring? (b) If the spring is used to shoot a 20-g pebble straight up in the air, how high will the pebble rise? (Hint: How much work will the spring be able to do on the pebble? How much potential energy will the pebble have when it gets to its maximum height?)

4. What is the kinetic energy of a 2.0-kg mass that has fallen 5.0 m?

5. A 10.0-kg object is raised 20.0 m and then dropped. When it has fallen 5.0 m find its (a) kinetic energy; (b) potential energy. Check your work by finding (c) the potential energy when the object was 20.0 m high.

6. A 2.0 oz. pebble is dropped from a bridge 1053 feet above the river below. Find the kinetic energy of the pebble as it hits the water after being dropped from the bridge.

7. A ball with a mass of 200 g strikes the hand of a catcher and is stopped in a distance of 0.50 m. The ball was traveling at 20 m/sec when it struck. (a) What was its kinetic energy? (b) How much work did it do on the hand of the catcher? (c) What became of the energy of the ball? (d) With what average force did it strike the hand?

8. How much work must be done on a 0.50-lb ball to give it a velocity of 50 ft/sec? If your hand moves 2.5 ft while throwing this ball, what is the average force that you apply?

9. A 5.0-kg stone falls for 10 sec. Find its kinetic energy (a) from its velocity; (b) from its loss of potential energy.

10. A pendulum clock is wound by raising a 2-lb weight 3 ft. It will run for 30 hr on one such winding. What is the power consumption of the clock?

11. A 1000-kg object falls 80.0 m to the ground and sinks 0.50 m into the ground. What was the average force of the impact?

B **12.** How many cubic feet of water per minute would have to fall from the top of a reservoir down to the water wheel 200 ft below in order to generate 1.0 kW of power, if none of the energy were wasted?

13. Show that energy is conserved in the collision of Problem 5, p. 52.

Discussion Questions

1. When you drop a ball it does not bounce back to the level from which you dropped it. Why?
2. The point was made in the chapter that potential energy must be measured relative to some specific level. Is the kinetic energy of an object also a relative quantity?

Chapter Summary

Work is done when a force acts through a distance. The work done is equal to the product of the force and the distance in the direction of the force. If the two are not in the same direction, then the work is equal to the distance times the component of the force in the direction of the distance. Work is measured in joules, ergs, foot · pounds, and kilowatt · hours.

Power measures the rate at which work is done. It is equal to the amount of work per unit of time. It is also equal to the product of a force and the speed of motion. Power can be measured in watts and horsepower.

Energy is defined as the ability to do work, and is measured in work units. Energy exists in various forms. Mechanical energy may be kinetic, the energy of motion; or potential, the energy of position or condition. Other forms of energy are heat, light, sound, and electrical energy, and the stored forms, chemical energy and matter. Energy may be changed from form to form, but may neither be created nor destroyed. This is known as the law of conservation of energy.

The energy possessed by an object is equal to the work done on it to put it into its position or condition or to give it motion. The potential energy of a raised weight is equal to the work done on it to raise it. The kinetic energy of a moving object is equal to the work done to bring it up from zero velocity to whatever velocity it has when the kinetic energy is calculated. As an object falls, its potential energy is converted to kinetic energy. The kinetic energy of a falling body can be calculated from its loss of potential energy; the kinetic energy of any body can be calculated from its mass and velocity. If an object does work on another object, it loses energy equal to the work done.

Vocabulary

work (*pp. 55, 56, 59*)
newton · meter (*p. 57*)
joule (*p. 57*)
dyne · centimeter (*p. 57*)

erg (*p. 57*)
foot · pound (*p. 57*)
component (*p. 59*)
power (*p. 61*)
horsepower (*p. 62*)
watt (*p. 62*)
kilowatt (*p. 62*)
kilowatt · hour (*p. 62*)
thrust (*p. 63*)
energy (*p. 64*)
kinetic energy (*p. 64*)
potential energy (*p. 64*)
mechanical energy (*p. 64*)
energy conversion (*p. 64*)
forms of energy (*p. 64*)
chemical energy (*p. 65*)
law of conservation of energy (*p. 65*)

Problems

Ⓐ **1.** A man ties a rope around a heavy rock and pulls with a force of 100 lb until he is exhausted, without succeeding in moving the rock. Find the work done on the rock.

2. A man exerts a horizontal force of 20 N to push a 10-kg table across a level floor a distance of 5.0 m. How much work does he do?

3. A 10-kg mass is lifted 50 m. How much work is done?

4. A man exerts a force of 30 lb to slide a 100-lb load up a slope. If the force is exerted along the slope and the load moves 20 ft along the slope, how much work is done on the load?

5. The wind blows on the sail of a boat with a force of 3000 N. The wind blows directly from the north, but the boat travels in a southeasterly direction at an angle of 120°, measured from north. If the boat moves 500 m, how much work is done on it?

6. A crane loads cars onto a freighter. Each car weighs 2500 lb and must be lifted 50 ft and then moved 40 ft horizontally. If the crane loads a car in 2.0 min, what is the average horsepower delivered by the crane?

7. The observation platform in the Husky Tower at Calgary, Alberta is 516 feet above street level. How much work is done by a 160 lb man in climbing from the street to this platform?

8. A 10-kg rock rolls down the side of a mountain, finally coming to rest at a point 1.0 km lower than its starting point. How much work did it do?

9. You are in an airplane 1 mi up, traveling at 240 mi/hr. Find (a) your kinetic energy with respect to the floor of the plane if you weigh 120 lb and your center of gravity is 2.0 ft above the floor; (b) your potential energy with respect to the floor of the plane; (c) your kinetic energy with respect to the earth; (d) your potential energy with respect to the earth.

10. A 20-g bullet travels with a velocity of 600 m/sec. How high will the bullet rise if it is shot vertically upward? Solve using energy ideas and check by using falling bodies ideas from Chapter 3. Assume that the friction of the air is unimportant.

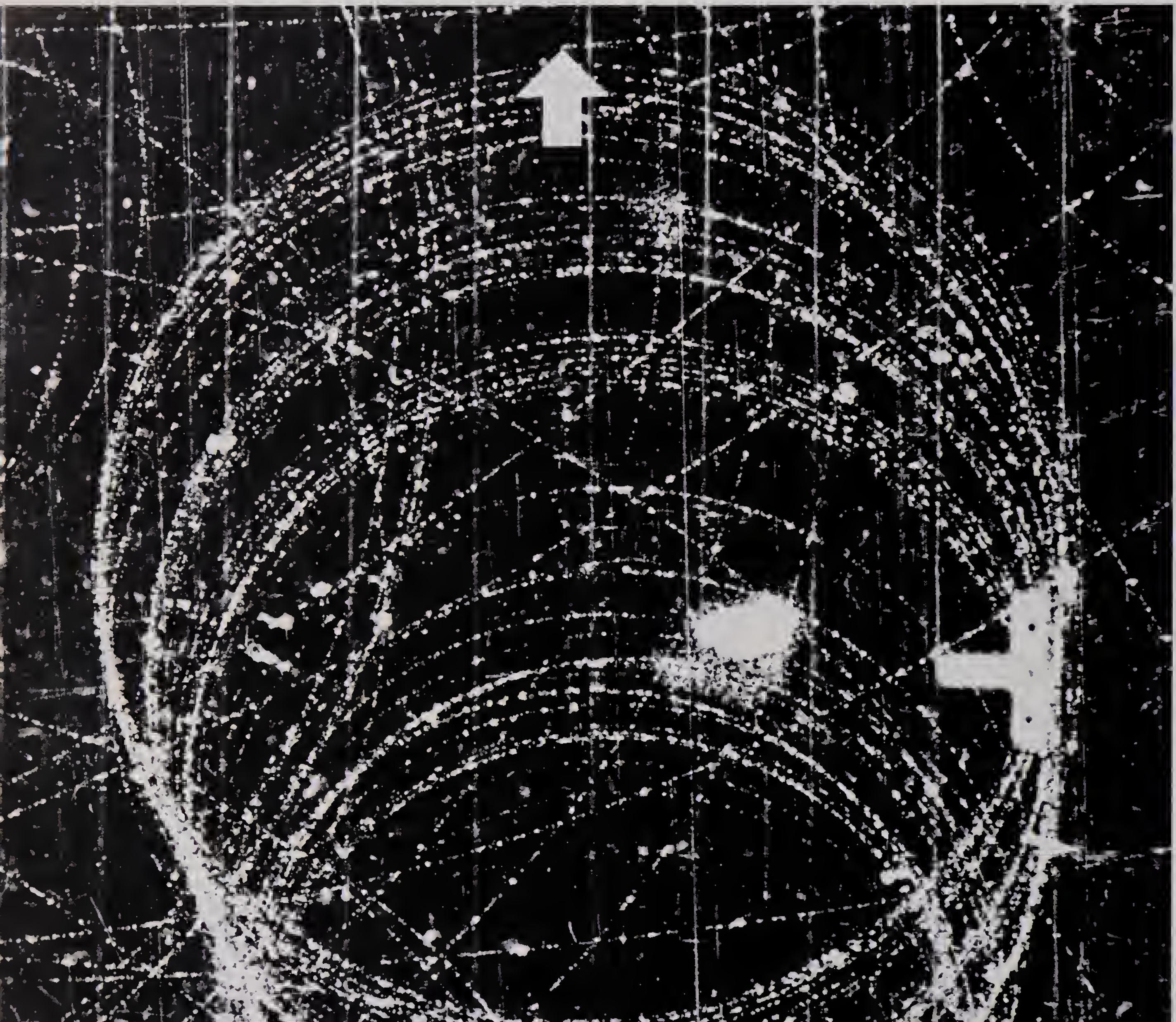
Ⓑ **11.** The purpose of this problem is to compare the work available to the average householder in his use of electricity with the work required to build the Great Pyramid at Giza in Egypt. The pyramid has a total weight of about 6,800,000 tons and is 450 ft high. The work to raise this amount of stone to its varying height in the pyramid is equal to the work done to raise all of it one quarter of the way to the top. If the average annual consumption of electricity is 2500 kWh, how many households would have to give up their quota to get the pyramid built in one year?

12. A 20-g bullet enters a block of wood at 300 m/sec and leaves it on the other side at 200 m/sec. If the block was 10 cm thick, what was the average force of the bullet as it passed through the wood?

Discussion Questions

1. If you drop a ball, are you doing work? Does the ball have work done on it?
2. Does your heart do work?
3. If a rocket has a constant thrust as it accelerates, is its power output constant? Why?
4. The truck in Fig. 3–7 actually has a greater power output than was calculated in the text. Why is this so?
5. Why is a homeowner billed for kilowatt hours instead of kilowatts?
6. If you lift a 1-kg book, is the weight of the book the force that does the work?
7. Compare the speed of a baseball after being hit by a bat with the speed of the ball as it approached the bat.

CHAPTER 4



Courtesy of Wilson M. Powell, Radiation Laboratory, University of California.

X-rays entered at the upper left but made no tracks because they are not charged particles. At the tip of the arrow a photon has been converted into two particles, which curve in opposite directions in the magnetic field. Measurements of the tracks indicate that the lower particle was an electron. The upper particle was a positron, which is exactly like an electron in mass but opposite in charge. Page 97 explains how scientists learn about invisible particles.

Matter and Energy

For almost 200 years after the death of Newton, his ideas represented the complete description of the physical behavior of matter in motion. So well established were these laws that physicists felt that research in the future would be largely devoted to measuring various constants (like G in the gravitation equation) with higher and higher accuracy. Albert Michelson wrote, "While it is never safe to affirm that the future of Physical Science has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established."

Then came an explosion of new discoveries that has made the twentieth century in science as exciting as the seventeenth of Galileo and Newton. The explosion started in the 1890's and continues today. Physicists found out that the mass of an object is not a constant, but grows when the energy of an object increases. Chemists during the nineteenth century had discovered that all matter is made up of a few more than ninety elements. Scientists now know that the elements are composed of tiny particles (see opposite page), many of them having electric charges. They have discovered how to change one element into another by using their knowledge of these elementary particles.

Many other discoveries have come. In this chapter you will learn about three of them: the relationship between mass and energy, the basic structure of matter, and how matter is changed from one form to another.

The Relationship Between Mass and Energy

4–1 Mass increases with velocity. Electrons are extremely tiny particles of matter. Millions of them rush down the length of a television tube at tremendous speed and crash into the screen at the end. This is what makes it glow and forms the picture. A television tube is one member of a family called cathode-ray tubes. With these tubes it is possible to learn a great deal about electrons and how they behave. Using a cathode-ray tube, a number of men found that when electrons travel at speeds of 20,000 miles a second and more, they have more inertia than they do when they are moving slowly. Mass is the measure of the inertia of a body, so it seemed as if the mass had increased.

This discovery had been predicted by

Albert Einstein in his special theory of relativity in 1905. According to this theory, at ordinary velocities the mass of an object remains so nearly constant that no change can be detected; but when the speed approaches that of light in a vacuum (1.86×10^5 mi/sec, or 3.00×10^8 m/sec), the mass is greatly increased. The speed of light in a vacuum is constant and is designated by the letter c.

The mass of an object that is not moving is called its **rest mass** (m_0). The mass of an object in motion is called its **relativistic mass** (m) and was given by Einstein as:*

$$m = \frac{m_0}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

where v is the speed of the moving object.

Now suppose that an object moves with a speed that is exactly 0.1 times the speed of light. It would be going at 1.86×10^4 mi/sec (3.00×10^7 m/sec), a speed fast enough to take the object three quarters of the way around the earth in one second. According to the Einstein law, what effect should this have on its mass?

$$m = \frac{m_0}{\sqrt{1 - \left(\frac{0.1c}{c}\right)^2}} = \frac{m_0}{\sqrt{1 - 0.01}}$$
$$= \frac{m_0}{\sqrt{0.99}} = \frac{m_0\sqrt{0.99}}{0.99}$$
$$= 1.005m_0$$

The relativistic mass in this case is not much greater than the rest mass, but the increase is measurable, as experiments with electrons have shown.

Now imagine that an electron is moving at exactly half the speed of light. In this case $v = 0.5\,c$, and $(v/c)^2$ becomes 0.25. Therefore

$$m = \frac{m_0}{\sqrt{0.75}}$$
$$= 1.15m_0$$

This is a 15 percent increase in mass. A 100-kg object moving at 9.3×10^4 mi/sec (1.5×10^8 m/sec) would have a mass of 115 kg.

Obviously the mass increases have not been enormous, even at the very high velocities imagined in the two examples just

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* Also called the Lorentz-Einstein law because it was derived independently by H. A. Lorentz and Albert Einstein.

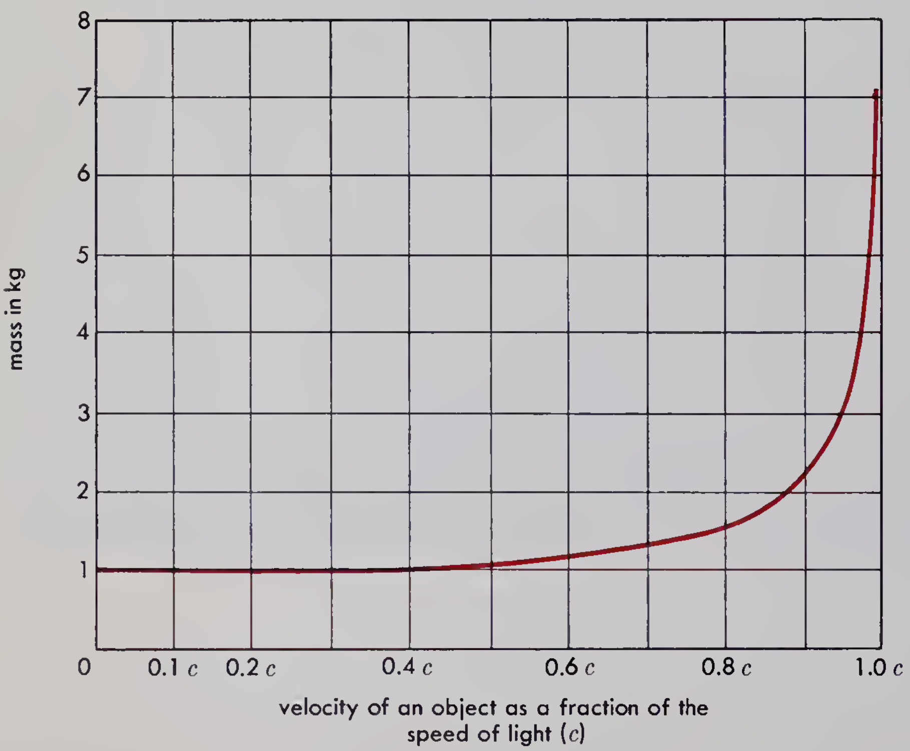


Figure 4–1 When an object is speeded up, its mass increases. The mass increases very slowly until its velocity approaches c, the velocity of light. The curve of the graph comes nearer and nearer to the line marked 1.0 c, but will never touch or cross it. The mass would be infinite if the velocity were equal to c.

used. For contrast, let $v = 0.98\,c$. Now $(v/c)^2$ becomes 0.96. Therefore

$$m = \frac{m_0}{\sqrt{0.04}}$$

$$m = 5m_0$$

Here, at last, is a mass change that is truly amazing. According to Einstein's law, if your mass is 70 kg sitting in a chair, then your mass would be 350 kg if you were to travel at 98 percent of the speed of light!

Has this mass change been checked with electrons? The results at this velocity agree fairly well with the Einstein prediction, but at such speeds the accuracy of the measurements is not as reliable as for lower speeds. Many thousands of checks on the Einstein law have been made, and they all agree very closely for speeds up to about 80 percent of the speed of light (149,000 mi/sec). At higher speeds there is still good agreement, but the experiments are less accurate. Figure 4–1 at the left is a graph of the Einstein law.

The fastest man-made objects to date are probably the instrument packages rocketed into space from the earth. They leave the earth at a speed of approximately 25,000 mi/hr (7 mi/sec). Matter at that speed should increase its mass by only three fourths of one ten-millionth of one percent if the Einstein law is correct. No wonder that for almost 200 years after Newton no one guessed that mass could change!

Do these new discoveries mean a rejection of Newton's laws of motion? By no means. For moving bodies, a slight correction must be made in the mass. However, this correction is so small that it can be called zero, except when the speed is very great. To date, speeds great enough to cause a measurable change in mass occur only with atomic particles.

However, no one says that Newton was mistaken or that his laws must be disregarded. Instead physicists now say that the new laws are more general, and they cover a larger variety of possible cases than did Newton's. As a matter of fact, the new laws (and there are more than the one about mass) agree with Newton's at low speeds.

4–2 A moving mass has a speed limit.

In the last section, the relativistic mass was calculated three times. Notice what happens to the denominator of the Einstein equation and to m as v increases:

v	Denominator of equation	m
$0.10c$	$\sqrt{0.99}$	$1.005m_0$
$0.50c$	$\sqrt{0.75}$	$1.15\ m_0$
$0.98c$	$\sqrt{0.04}$	$5.00\ m_0$

As v increases, the denominator decreases and m increases.

Now think about the situation when an object moves with the speed of light. Then $v = c$.

$$m = \frac{m_0}{\sqrt{1 - \left(\frac{c}{c}\right)^2}} = \frac{m_0}{\sqrt{1 - 1}} = \frac{m_0}{0}$$

You have probably been taught that you cannot divide a number by zero. Usually this is so, but in this case it is possible to find some kind of meaning for $m_0/0$. In order to do this, see what happens when v gets larger than $0.98\,c$:

v	Denominator of equation	m
$0.99c$	$\sqrt{0.02}$	$7.07m_0$
$0.999c$	$\sqrt{0.002}$	$22.4\ m_0$
$0.9999c$	$\sqrt{0.0002}$	$70.7\ m_0$
$0.99999c$	$\sqrt{0.00002}$	$224.\ m_0$

The denominator of the equation is getting closer and closer to zero, and the value of m is getting larger and larger. At this point a mathematician begins to talk about what he calls the *limits* of the sequence of numbers in each column. He reasons: As v approaches the speed of light, what value does the denominator of the equation approach as a limit? Obviously it is approaching zero. At the same time, what value does m approach as a limit? We see that m gets bigger and bigger and there is no apparent end to its increase. Therefore, m can grow to a size that is infinitely large.

The mathematician uses the symbol ∞ to represent infinity. In this case:

$$\text{As } v \longrightarrow c, \quad m \longrightarrow \infty$$

Read "approaches" for the arrows: As v approaches c, m approaches infinity.

So much for mathematics. Now consider what Einstein's equation means about the physics of the situation. It states that when an object is accelerated, its mass increases. Now you know that in order to accelerate an object, you must apply an unbalanced force. Here the form in which Newton expressed his second law (see Chapter 2, p. 34) is probably the most helpful:

$$F = \frac{\Delta(mv)}{\Delta t}$$

The force is proportional to the rate at which the momentum (mv) is changing.

Unlike the situations considered in Chapter 2, in this case not only is the speed increasing, but the mass is also growing. Therefore, more force is needed than in the case where only the speed increased. But Einstein's equation says that as the speed becomes that of light the mass becomes infinitely large. If that is the case, then the force needed to work with such a mass would itself be infinitely large. The situation becomes an impossible one. It is for this reason that physicists have concluded that the speed of light in a vacuum, 1.86×10^5 mi/sec, or 3.00×10^8 m/sec, probably is the speed limit for a moving mass.

Notice the word *probably* in the last sentence. It is used because the equation for relativistic mass has been checked for many values of v, but not accurately for all of the higher ones. Therefore it cannot be said with absolute certainty that the equation is correct for *all* values of v. But all of the evidence gathered so far shows that this is a good equation, and a scientist draws conclusions from evidence. Therefore physicists presently believe that no object can move either at the speed of light or faster than it. If, in the future, they were to obtain evidence contrary to this, they would be willing to change their opinions.

4–3 Einstein determines the energy equivalent of the change in mass. In Chapter 3 (pages 67–68) you learned that the kinetic energy of a moving object is equal to the work done to accelerate it from rest. An equation was derived for kinetic energy in terms of velocity: $E_k = \frac{1}{2} mv^2$. However, the assumption was made that the mass was not changing when the object accelerated — a good enough assumption for ordinary speeds.

When Einstein concluded that the mass of an accelerating object increases with its speed, he found it necessary to derive a new kinetic energy equation. For this he needed to use calculus, and the derivation is complicated. However, the final equation is surprisingly simple:

$$E_k = (m - m_0)c^2$$

The kinetic energy of a moving object equals its increase in mass multiplied by the square of the speed of light. The equation may also be written thus:

$$\Delta E = \Delta mc^2$$

In this form, ΔE represents energy added to a mass and $\Delta m = m - m_0$, the change in mass. ΔE is called the energy equivalent of the mass change. This formula is often written as $E = mc^2$.

4–4 Mass is stored energy. At this point Einstein drew a conclusion that, at the time, seemed incredible. He said that matter and energy are the same thing, that matter is another form of energy. His reasoning was something like this:

> You cannot increase the kinetic energy of an object without increasing its mass proportionately.
>
> The energy put into an object is therefore stored in it as an increase in mass.
>
> Mass is stored energy.

If mass is stored energy, then what about the rest mass of an object? The object has no energy of motion. Is rest mass stored energy too? Einstein said that it was, and that if scientists could invent a way to destroy the rest mass of an object, they could get energy out of it. They could convert mass into active energy.

As a result of this thinking, Einstein gave a much broader meaning to $\Delta E = \Delta mc^2$. ΔE is the energy involved whenever the mass of an object changes. It may be kinetic energy, as in the case of a fast-moving object. On the other hand, if you succeeded in destroying some of the rest mass of an object, you might turn it into heat, light, electricity, or some other energy form.

Einstein was a theoretical physicist. He used the results of experiments performed by others, such as the ones with cathode-ray tubes that showed that mass increases as velocity increases. He analyzed the results mathematically and drew conclusions like the one about mass and energy. Then he suggested ways in which his conclusions might be tested.

It was impossible to test some of his conclusions at the time because no one could devise a method of doing it. The mass-energy idea was finally proved experimentally in 1932 on a small scale in the laboratory. Today the idea is being put into practical use in nuclear power plants and ship propulsion systems.

Self Check

1. At a speed of 60 mi/hr is the mass of a car greater than when it is at rest?
2. How has the idea that mass changes with change in speed been checked?
3. What order of speed must an object possess in order for its mass change to be observable?
4. What theory is concerned with change of mass with speed? Who is responsible for the theory? Give the date.
5. What is the mass of a body called when it is not moving? When it is moving?
6. What is probably the speed limit for moving objects?
7. Why is it unlikely that any object can go faster than this or even as fast as this?
8. If you knew the mass increase of a moving object, how could you calculate its kinetic energy?
9. What conclusion did Einstein draw about the nature of matter and energy?
10. What evidence is there that Einstein was right?

Problems

Ⓐ 1. What is the relativistic mass at a speed of 0.80 c of an object with a rest mass of 1.0 kg?

Ⓑ 2. What is the speed in m/sec and in mi/sec of a particle with a relativistic mass exactly twice 3 its rest mass? Determine the answer to three significant digits.

3. Check the values for m given in the chart on p.75 for very high speeds.

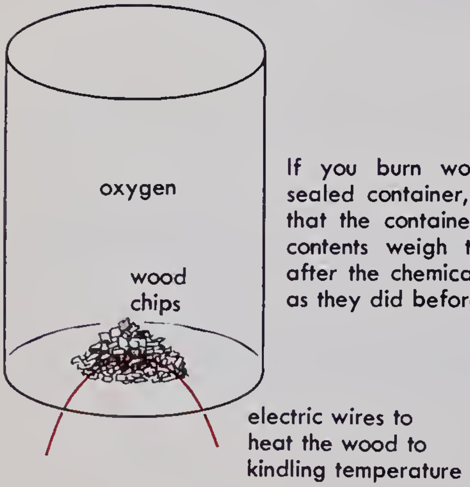
Conservation of Mass-Energy

4–5 Matter, like energy, is conserved. If you burn a piece of wood, you find that the ashes weigh less than the wood did. However, if you put the wood inside a closed container of air so that no gas can escape, and if you provide a means of igniting it, you will find that the container and its contents weigh the same after the burning as before (Fig. 4–2).

Hundreds of chemical changes like this were investigated by scientists of the eighteenth and nineteenth centuries. In every case, careful weighing showed that the weight of all the substances present at the beginning was equal to the weight of all the substances present at the end. Therefore, the chemists concluded that it was possible to rearrange matter to make new chemical combinations, but that in the process matter was not created nor destroyed. They called this the **law of conservation of matter**

4–6 Mass can be converted to energy. When the wood burns in the closed container, energy in the form of light and heat is given off, and some of this energy escapes through the container walls. If Einstein was right when he said that mass and energy are really the same thing, then the container and wood ashes should weigh less after the burning than before. The mass represented by the amount of energy given off by a chemical change like this is so small, however, that the best balance ever built cannot detect it.

Figure 4–2 The law of conservation of matter.



If you burn wood in a sealed container, you find that the container and its contents weigh the same after the chemical change as they did before.

Nuclear changes such as those in nuclear power plants produce much more energy per gram of fuel than burning does. Physicists have weighed small quantities of matter before and after a nuclear change. They have found that the mass is less after the change, and that the loss in mass has produced energy exactly equal to Δmc^2, where Δm is the loss in mass.

Suppose that you have a method for converting mass to energy. The following example shows how to calculate how much energy would be obtained from a given mass. Study Example 1 below.

EXAMPLE 1

How much energy is yielded by exactly 1 g of mass when it is completely converted to energy? (One teaspoonful of water weighs almost 5 g.)

Given: m (change in mass) $= 1 \text{ g} = 10^{-3}$ kg exactly

To find: Energy produced by this change in mass

Solution:

$$\begin{aligned} E &= \Delta mc^2 \\ &= 10^{-3}\ \text{kg} \times (3.00 \times 10^8\ \text{m/sec})^2 \\ &= 10^{-3}\ \text{kg} \times 9.00 \times 10^{16}\ \text{m}^2/\text{sec}^2 \\ &= 9.00 \times 10^{13}\ \text{kg·m}^2/\text{sec}^2 \\ &= 9.00 \times 10^{13}\ \text{J} \\ &= 9.00 \times 10^{13}\ \text{J} \times \frac{1\ \text{kWh}}{3.60 \times 10^{6}\ \text{J}} \\ &= 2.50 \times 10^{7}\ \text{kWh, Answer} \end{aligned}$$

This is enough energy to supply 10,000 homes with all the electricity they require for a year. You would have to burn nearly

3,000,000 kg of coal to get as much energy as comes from 1 g of converted mass. It is no wonder that the search for methods of releasing energy from matter has been made. These conversions, however, are not as simple as they sound. In this problem it was assumed that *all* of the 1 g of matter was converted to energy. There is no method known that will convert all of a given quantity of matter into energy. In present nuclear reactions only a fraction of one per cent of the mass is converted to energy.

4–7 Mass-energy is conserved. The law of conservation of matter has been found to be imperfect. Is the law of conservation of energy also imperfect? This depends on how you think about mass. If it is something different from energy, then the law of conservation of energy is not correct. However, many scientists prefer to think that mass is a form of energy, and they calculate its energy equivalent from the equation, $E = mc^2$. Here m represents the total mass, including the rest mass, of the object, and E, the total energy. If this is the case, then when conversions take place, energy in the form of mass might become light or heat energy, with nothing really lost; or light energy might become mass, again with nothing really lost. Then the law of conservation of energy is called the **law of conservation of mass-energy** Energy and mass can be converted from one form to another, but when this happens, the total quantity of mass-energy remains the same.

Self Check

1. What is the law of conservation of matter?
2. What kinds of experiments led scientists to accept this law?
3. In what way is the law imperfect?
4. Why is it not easy to measure the imperfections of this law?
5. What equation can be used to determine the energy produced by conversion of mass into energy?
6. Compare the energy produced by a chemical change such as burning with the energy produced by conversion of mass into energy.
7. What is the energy equivalent of mass?
8. What is meant by mass-energy?
9. What is the law of conservation of mass-energy?

Problems

B 1. In a recent year the total amount of electrical energy used in Canada was approximately 1.34×10^{11} kwh. If this could have been supplied by the conversion of mass into energy, how much mass would have been needed? Find the answer to the nearest kilogram.

2. The distance to the nearest star other than our sun is 4.3 light years. Its light takes that long to reach the earth. You could go there and back in 8.6 years if you could travel with the speed of light. Since this is impossible, take a more reasonable speed, 0.2 times the speed of light, for example. At this speed, you could get there and back in 43 years. Suppose that you take the trip in a spaceship with a rest mass of 100,000 kg. How much energy in kilowatt · hours would be required to accelerate the ship to the necessary speed? Compare this with the annual consumption of electrical energy in Canada as given in problem 1.

Discussion Questions

1. Compare the mass of the sugar in a plant leaf with the masses of the carbon, oxygen, and hydrogen that were used by the plant to make the sugar.
2. This chapter so far has largely been concerned with the conversion of matter into energy. Can energy also be converted into matter?

The Electrical Nature of Matter

> "Observation shows me," said Sherlock Holmes, "that you have been to the Wigmore Street Post Office this morning."
>
> "Right!" said I. "But I confess that I don't see how you arrived at it. It was a sudden impulse upon my part, and I have mentioned it to no one."
>
> "It is simplicity itself," he remarked, chuckling at my surprise — "so absurdly simple that an explanation is superfluous. . . . Observation tells me that you have a little reddish mud adhering to your instep. Just opposite the Wigmore Street Office they have taken up the pavement and thrown up some earth which lies in such a way that it is difficult to avoid treading in it on entering. The earth is of this peculiar reddish tint which is found, as far as I know, nowhere else in the neighborhood."
>
> *The Sign of the Four* by A. Conan Doyle

Modern scientists behave much like Sherlock Holmes when they try to describe the basic nature of matter. They use indirect evidence to get a mental picture of things that they cannot observe directly. They study tracks left by invisible electrons speeding through a cloud chamber (Fig. 4–3). They fire invisible helium atoms at a metal needle and find out how they bounce by observing the flashes made when the atoms hit a fluorescent screen (Fig. 4–4).

You will never see an electron or an atom. They are too small. One cubic centimeter of air contains about 54,000,000,000,000,000,000 (5.4×10^{19}) atoms. This is almost twenty billion times the population of the earth. Most atmospheric atoms have about seven or eight electrons as part of their structure. Despite the fact that atoms are too small to be seen, so conclusive is the indirect evidence that scientists have no doubts that they exist. Scientists count atoms and electrons, weigh them, determine their average speeds and distances apart. More is known about the nature of invisible atoms and electrons and how they behave than about the nature and behavior of the much more easily visible people, who inhabit the earth.

4–8 Producing electric charges is an ancient activity. Six centuries before the

Figure 4–3 The white tracks in this cloud chamber photograph are tiny drops of water that condensed along the paths of electrons. You cannot see the electrons, but you can see where they have been.

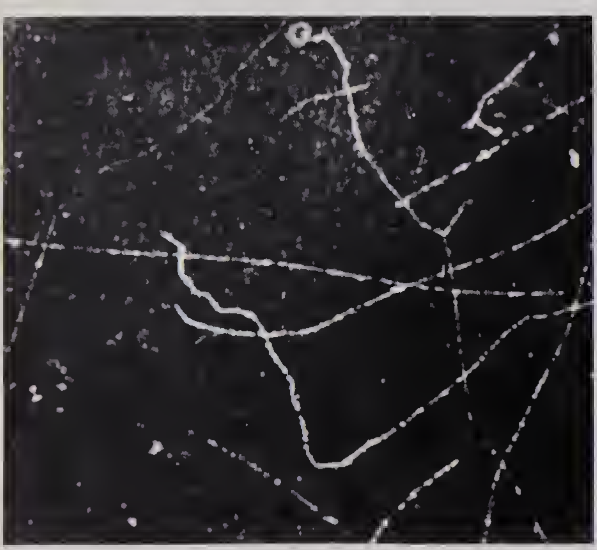
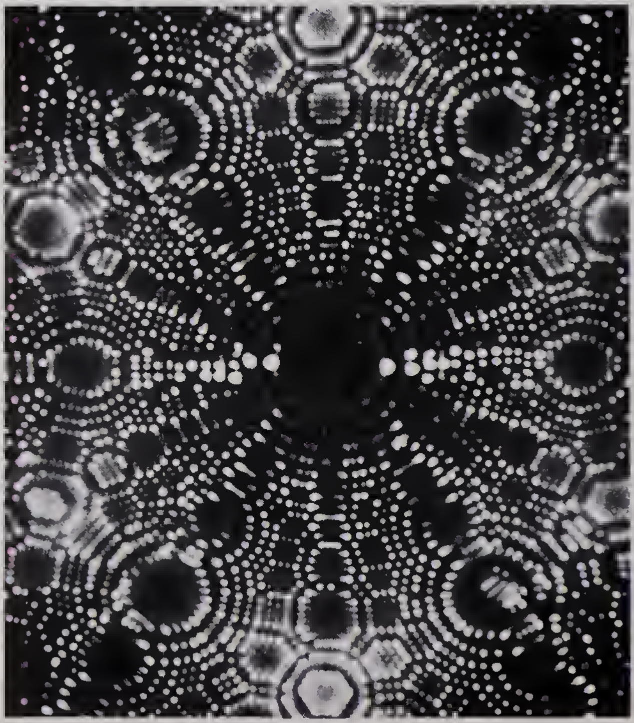


Figure 4–4 This photograph shows how the atoms are arranged in a crystal of tungsten. The enlargement in this picture is about 1,350,000 diameters.



a. Two strips of vinyl plastic can be charged by rubbing them briskly with three fingers.

b. As a result of being charged, the two strips repel each other.

Figure **4–5**

Christian era, a Greek scholar named Thales is reported to have described a phenomenon which may have been known many centuries before his time. He pointed out that amber, which might be called a natural plastic, has the ability when rubbed to attract small, light objects. The Greek word for amber was *elektron*, from which have come our modern terms *electricity* and *electron*.

Other electrical phenomena, such as lightning and northern lights, have also been known for thousands of years. Only in the last 200 years, however, has man begun to understand that all of these are related and are a result of the fact that matter is electrical in nature.

When you comb your hair with a plastic comb, your hair clings to the comb. A plastic pen rubbed on wool clothing attracts bits of paper. An inflated rubber balloon or a piece of paper rubbed on the wall will often stick. All of these are examples of attraction between **static** (stationary) **electric charges**.

The **electrostatic force**, the force between static charges, may also be one of repulsion. To illustrate this, rub two strips of thin vinyl plastic with three fingers, as is shown in Fig. 4–5a. After a few brisk strokes, the strips repel each other and stand out from one another, as in Fig. 4–5b.

Objects that have been electrified by rubbing may produce small electric sparks. You may have noticed this when you walk across a rug and then touch some metal object or another person. Girls combing their hair often hear it crackle due to the many tiny sparks they have produced. If this is done in a dark room, you may see the sparks. Special electrostatic generators can produce large charges by rubbing. Man-made lightning bolts jump 50 ft or more from such generators.

All of these phenomena are more readily observed in dry weather or in the dry air of a heated house in winter than they are in moist air, for the charge tends to leak off the rubbed object when the air is humid.

4–9 There are two kinds of electric charge. So far, these simple observations show that when objects are electrified by rubbing, sometimes there is attraction and sometimes repulsion. The next step is to make a more scientific investigation, using very simple equipment.

Rub strips of vinyl plastic as shown in Fig. 4–5a, and clip them to a hanging string (Fig. 4–6a). The two charged strips repel each other. Since both were treated in the same way, they have the same kind of charge. Call it charge A. Obviously charge A on one strip repels charge A on the other.

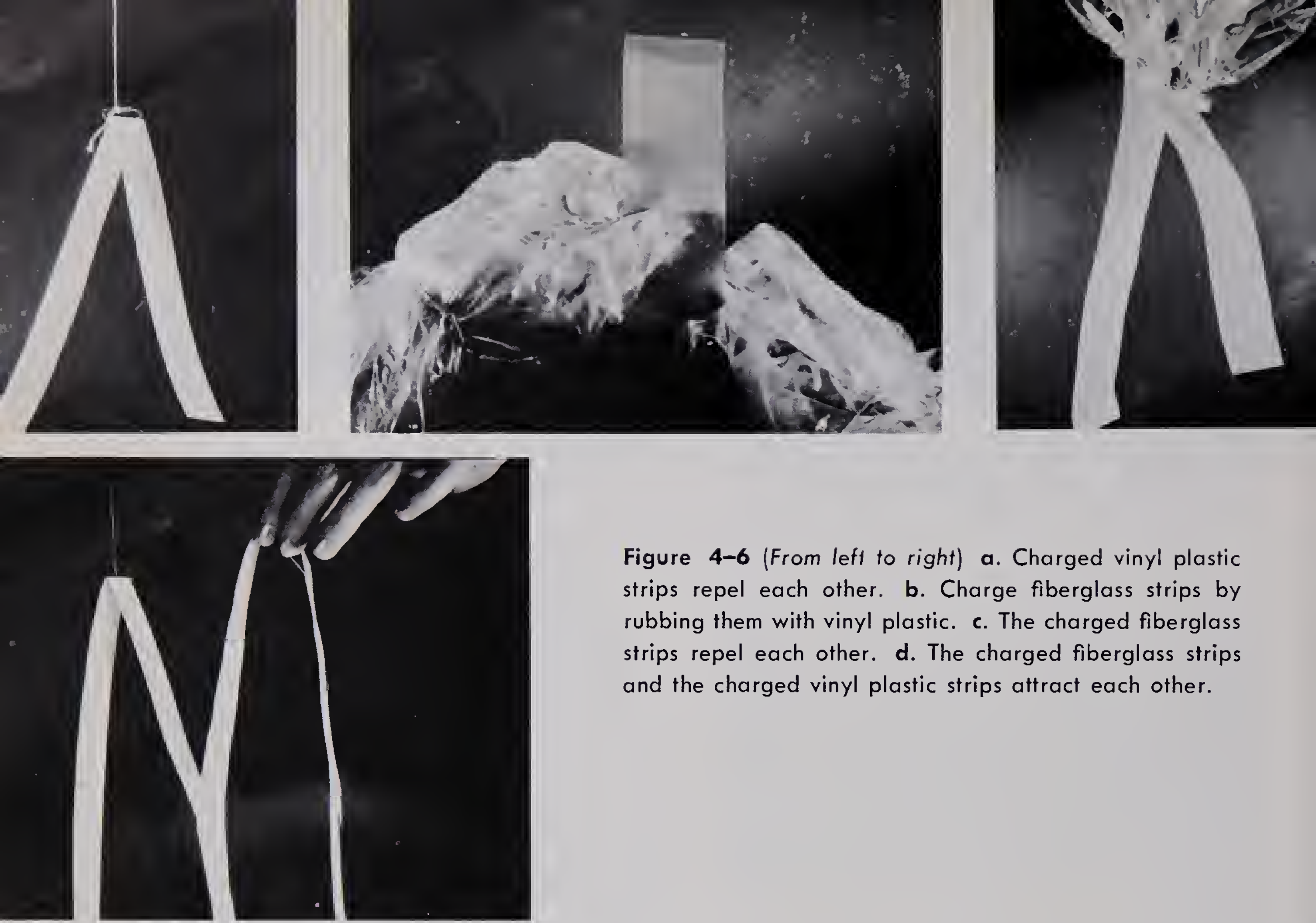


Figure 4–6 *(From left to right)* **a.** Charged vinyl plastic strips repel each other. **b.** Charge fiberglass strips by rubbing them with vinyl plastic. **c.** The charged fiberglass strips repel each other. **d.** The charged fiberglass strips and the charged vinyl plastic strips attract each other.

Now use two strips of thin fiberglass cloth from an old window curtain. Cover one hand completely with a plastic bag and use this hand to rub the strips (Fig. 4–6b). These charged strips also repel each other (Fig. 4–6c). Since they were treated alike, the charge on the two fiberglass strips must be the same. What you do not know is whether it is the same kind as the charge on the plastic. Therefore call it charge B. Obviously charge B on one strip repels charge B on the other.

Next bring the fiberglass strips near the hanging plastic ones (Fig. 4–6d). There is attraction between the two kinds of strips. Charge A and charge B attract each other. They must be different kinds of charges because if they were alike they would repel each other.

People have experimented with many kinds of materials, but they have never found more than these two kinds of charge. Always when the charges are alike, they repel each other, and when they are unlike they attract each other.

Before the time of Benjamin Franklin, various names were given to the two kinds of charges. One investigator called the charge that forms on amber *resinous* and the charge that forms on glass *vitreous*. Franklin called them *negative* and *positive*, names we still use. The negative charge is the one produced on vinyl plastic when you rub it with your hand. The positive charge is the one produced on the fiberglass when you rub it with plastic.

To explain what happens when objects become charged, scientists set up suggested explanations, or hypotheses. One hypothesis was that of Benjamin Franklin, who suggested that there might be an electrical fluid in every object. According to this hypothesis, when two objects are rubbed together, some of the "fluid" passes from one object to the other. The one with the extra supply of "fluid" becomes positively charged; the one with the decreased supply, negatively charged.

When various hypotheses are put forth to account for some observations, scientists prefer the one that is simple, fits the facts, and leads to new ideas and experiments that work in practice. The hypothesis which is accepted today is somewhat like that of Franklin, but reflects an increased understanding of the nature of matter.

4–10 Electrons are gained or lost. According to this hypothesis, all matter is largely made of tiny particles called **electrons**, **protons**, and **neutrons**. Protons and neutrons are nearly 2000 times as heavy as electrons, but all are extremely small. An electron, for example, has a rest mass of 9.1×10^{-31} kg. Protons have a positive charge; electrons have a negative charge; neutrons have no charge.

Despite their difference in mass, protons and electrons have charges of equal magnitude. Since these charges are of opposite natures as well as of equal magnitude, one electron neutralizes one proton. An uncharged, or electrically neutral, object contains protons and electrons in equal numbers.

Electrons, having less mass than protons, can be moved more readily. An object acquires a charge when some electrons have moved into or out of it. Material that gains electrons becomes negatively charged; material that loses electrons becomes positively charged. (This is the reverse of Franklin's idea.) Actually only a small fraction of the electrons are lost from the object that becomes positively charged.

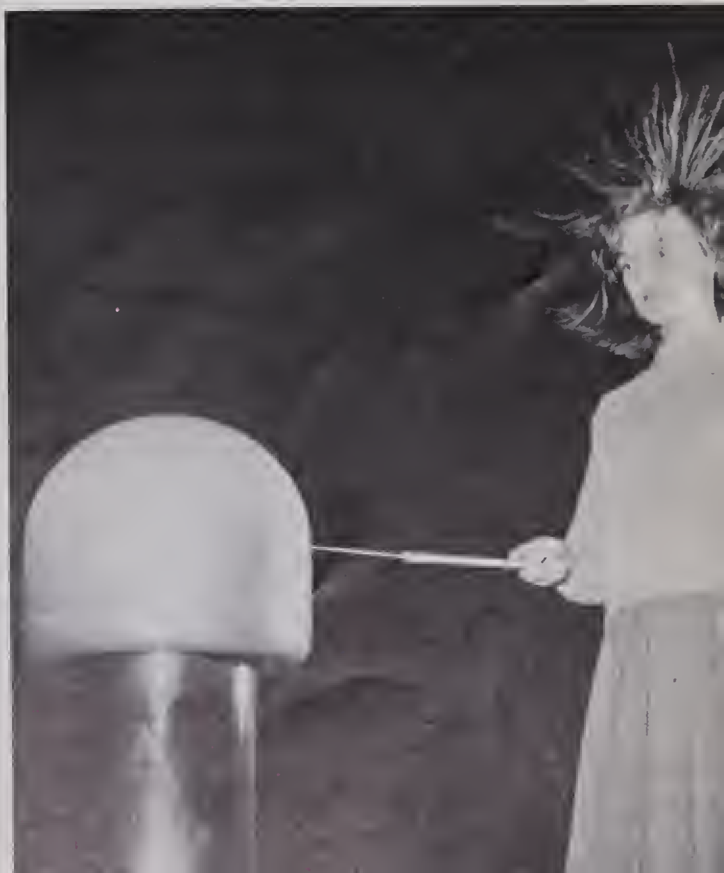
Hair that has lost electrons when you have combed it vigorously bears a positive charge, while the comb itself has gained electrons and is therefore negative. Because unlike charges attract each other, the hair tends to stick to the comb. Each individual hair, however, has a positive charge. Therefore, they all repel each other, as anyone knows who has brushed dry hair on a dry day (Fig. 4–7).

4–11 Electric charge is conserved. When you charge a body by rubbing it, the charge is not something newly created. It was always there. When you comb your hair, the hair loses electrons and the comb gains them. No new electrons are created. They are merely moved from one material to the other.

It is impossible to charge one object negatively without at the same time charging another positively to the same degree. The two objects neutralize each other when they are brought together. This idea is expressed as the law of conservation of charge: Electric charge can be neither created nor destroyed.

This statement of the law is not entirely satisfactory, however. Sometimes a neutron

Figure 4–7 The girl in this picture is highly charged with electricity. Because all of the charge is of the same kind, the hairs on her head repel each other and are repelled by the rest of her body. Therefore they stand on end.



is changed into two particles, an electron and a proton. Perhaps the positive and negative charges were there all the time and were merely neutralizing each other in the neutron. On the other hand, perhaps a pair of charges is "created" from the neutron. The important thing to notice, however, is that equal amounts of positive and negative charge appeared. Therefore, the total charge did not change. The neutron at the start had zero charge. The proton and electron at the end have a combined charge of zero. If they rejoin to form a neutron, again the total charge is unchanged.

Another fact to be noted is that when energy is converted to mass, charged particles may be produced, but they are always produced in pairs, one positive and one negative.

A more accurate statement of the **law of conservation of charge** is this: It is impossible to produce or destroy a positive charge without at the same time producing or destroying a negative charge of equal magnitude, that is, the total electrical charge of the universe is constant.

4–12 Coulomb measures electrostatic force. If you have been doing some of the experiments suggested in this chapter, you have probably noticed that electrostatic forces are affected by distance. You can observe this in greater detail by another experiment with charged rubber balloons. For example, charge two balloons and hang them from fine threads several inches apart, as in Fig. 4–8. You will notice that the balloons force the strings slightly away from the vertical. However, as the balloons are moved closer together, they force the strings farther and farther from the vertical. This clearly indicates that the repelling force between them increases as the distance between them decreases.

Just how does the force between charged objects change when the distance changes? You might make measurements on the balloons in Fig. 4–8 to answer this question. A more accurate method was invented by Charles Coulomb, a Frenchman who was interested in electricity. The apparatus that he used in 1785 is shown in Fig. 4–9. His results are shown on the top of p. 85.

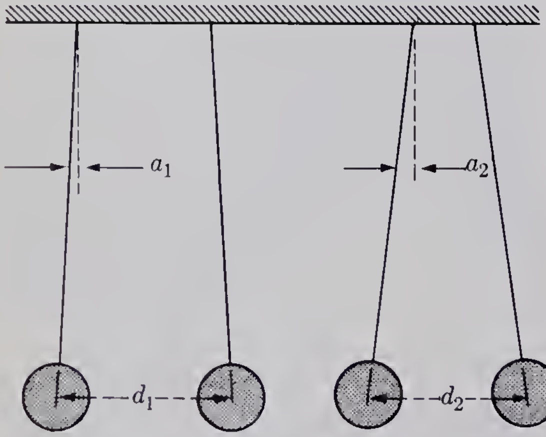


Figure 4–8 The balloons at the left have been charged and repel each other slightly. As they are brought closer together, the force of repulsion increases, and the angle a increases. The force of repulsion can be calculated from the weight of the balloons and the angle a. By this method it is possible to check the inverse square law.

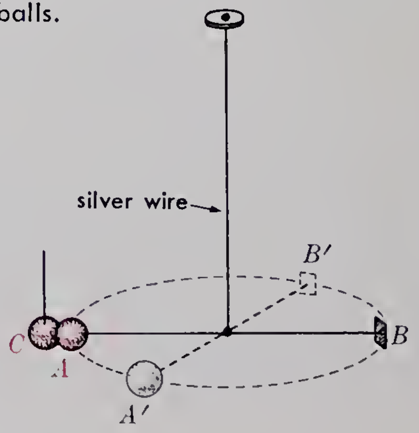


Figure 4–9 A diagram of Coulomb's apparatus. AB was a stiffly waxed thread or a straw. At end A was a small pith ball, and at end B was a piece of paper just heavy enough to balance the system. C is another pith ball, fixed in place, and just touching A. When he put charges of the same kind on A and C, A swung away because of repulsion of like charges. The angle of the swing told Coulomb how big the force was between the pith balls.

What Coulomb did.	What happened.	What angle did balls form?	What force held them apart?
Charged *A* and C.	They swung apart.	36°	0.0003 grains
Twisted the wire to get *A* and C closer.	*A* and C moved closer.	18°	0.0012 grains
Twisted the wire again.	*A* and C moved still closer.	8.5°	0.0047 grains

Coulomb measured his forces in grains, a tiny unit of weight equal to 1/7000 lb. He knew that the force that held the balls apart at a 36° angle was 0.0003 grains because he had previously measured how much force it would take to twist the silver wire that much. In order to get the balls back to 18° and later to 8.5°, he had to twist the wire even more, and he knew from previous measurements how much force this took.

When the balls moved in from 36° to 18°, their distance apart was approximately one-half as great. Notice what happened to the force. It became four times as great. Next, he moved the balls in to 8.5°, approximately halving the distance. Again, the force became almost four times as great. From such experiments Coulomb concluded that the inverse square law works with electrical forces, just as it does with gravitational forces. He checked the law for the case when the two balls had unlike charges and were attracting each other. Again the inverse square law seemed valid.

He reasoned that the force must also be due to the size of the charges. His conclusions, known as **Coulomb's law**, states: The electrostatic force between two charged objects is directly proportional to the product of the charges and inversely proportional to the square of the distance between them. Expressed mathematically:

$$F = k\frac{Q_1 Q_2}{s^2}$$

where F is the force between the charges Q_1 and Q_2, s is their distance apart, and k is a proportionality constant whose value depends on the units used. Coulomb's law holds precisely only if the charges have a tiny diameter compared with the distance between them. If the charge is spread out, the law must be modified.

The unit of charge used in the mks system is called the **coulomb** (**C**). One coulomb is equal to the charge of 6.24×10^{18} electrons. If this unit is used for Q_1 and Q_2, and if distance is measured in meters and force in newtons, then the value of k is found by experiment to be 9.0×10^9 $\text{N}\cdot\text{m}^2/\text{C}^2$. See Example 2 below.

EXAMPLE 2

If two tiny objects having charges of 1.0 C could be placed 1.0 m apart, what would be the force between them?

Given: $Q_1 = 1.0\text{ C}$ $\quad Q_2 = 1.0\text{ C}$

$d = 1.0\text{ m}$ $\quad k = 9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2$

To find: F

Solution: $F = k\dfrac{Q_1 Q_2}{s^2}$

$$= \frac{9.0 \times 10^9\ \text{N}\cdot\text{m}^2}{\text{C}^2} \times \frac{1.0\text{ C} \times 1.0\text{ C}}{1.0\text{ m}^2}$$

$$= 9.0 \times 10^9\ \text{N, Answer}$$

Since 9.8 N equal 1 kgf, this answer is over 900,000,000 kgf, or slightly more than a million tons of force. Obviously the coulomb is a very large unit of charge, so large that it would be impracticable to bring two like charges of one coulomb this close together.

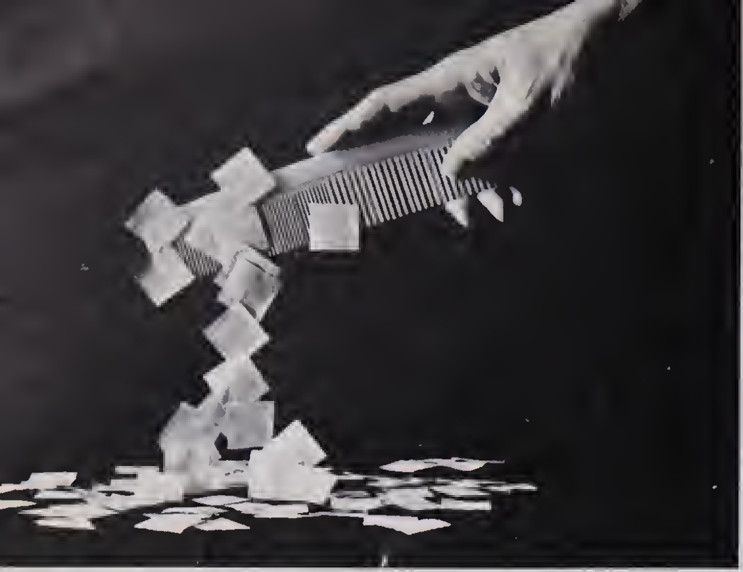


Figure 4–10 The electrostatic attraction between the charged comb and the pieces of paper is greater than the gravitational attraction of the earth for the paper.

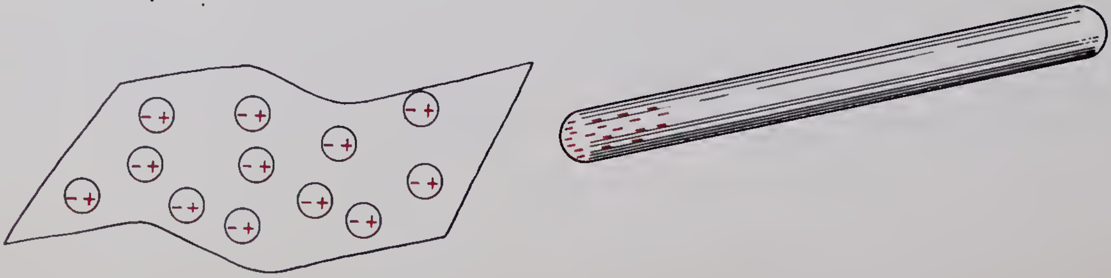
Although Coulomb's law is very similar to the gravitation law, the forces involved are quite different in size. Look, for example, at the photograph in Fig. 4–10. The comb has been charged by being run through its owner's hair a few times. A tug of war is going on, however peaceful the picture may look. The tug of war is between the gravitational pull of the earth and the electrostatic pull of the extra electrons on the comb. Obviously the electrons are winning the struggle. Compared with the mass of the earth, the mass of the comb is very small; the mass of the electrons in the charge on the comb is even smaller. Yet this small mass of electrons can produce an electrostatic force that is greater than the gravitational pull of the whole earth on the pieces of paper. The electrostatic forces between charges are enormously greater than the gravitational forces between them.

4–13 Objects can be charged by induction. Combed hair is attracted to a comb because they have unlike charges; two similar pieces of plastic rubbed with the hand repel each other because they have like charges. But how can a charged object, such as the comb of Fig. 4–10, attract an uncharged, or neutral, object, such as a bit of paper, and how can a charged balloon cling to an uncharged wall?

To understand the answers, you need to know more about the modern theory of the structure of matter. Electrons, protons, and neutrons are parts of **atoms**, the tiny building blocks of matter. The number of protons in an atom is the same as the number of electrons, making the atom neutral. As you have learned, it is possible by rubbing to remove some of the electrons from some kinds of atoms. When you comb your hair, you rub electrons off the atoms of your hair, leaving some of the hair atoms with a positive charge. The rubbed-off electrons cling to some of the comb atoms, giving them a negative charge.

Now you are ready to understand what happens when a charged rod picks up neutral bits of paper. As the negatively charged rod approaches the paper, it repels the electrons in each paper atom to the far side of the atom, as shown in Fig. 4–11. Notice that no electrons have been added or removed. The overall effect of this arrangement is to have the paper as a whole electrically neutral. However, the surface layer nearest the charged rod contains the positive sides of the atoms, while the far surface contains the negative sides of the

Figure 4–11 Under the influence of the charged rod, the atoms are oriented as shown below. The net effect is to place a positive charge on the right end of the paper and a negative charge at the left end. As a result, the force of attraction is greater than the force of repulsion.



other atoms. The positive surface is nearer the negatively charged rod than is the negative surface. Hence the force of attraction is greater than the force of repulsion, and the piece of paper is attracted toward the charged rod.

The bit of paper is, taken as a whole, electrically neutral, but its charges have been redistributed. Furthermore, this has occurred without there being any contact between the rod and the paper. The surface of the paper has been **charged by induction**. When the charged rod is removed, the induced surface charges disappear. Sometimes a charged rod attracts a piece of paper in this way and the paper clings to the rod. Suddenly the paper shoots off from the rod. This happens because the paper, once it touches the rod, may acquire a negative **charge by conduction** and is repelled by the negative rod.

4–14 Electrons move more freely in some substances than in others. The rod in Fig. 4–12 has been rubbed with fur at one end only. This end attracts bits of paper, but the other end does not. You know that the rubbed end has extra electrons, and you also know that electrons repel each other. If the electrons were free to move, then the repulsion should push them apart as far as possible, and there should be a negative charge all over the rod. Apparently the atoms of the rod are of a kind that do not allow this free movement. A substance in which electrons flow with difficulty because the electrons of the substance are tightly bound to the atoms is called an **insulator**. Rubber, paper, sulfur, plastic, wood, glass, and porcelain are all good insulators.

In metals, on the other hand, although the atoms hold most of their electrons tightly, each atom has one or more electrons that are not tightly held. These are called **free electrons**. A substance in which electrons flow with ease because there are many free electrons is called a **conductor**. If you charge one end of a metal rod with extra electrons, some of them will move toward the other end, repelling free electrons ahead of them, and soon the whole rod is charged.

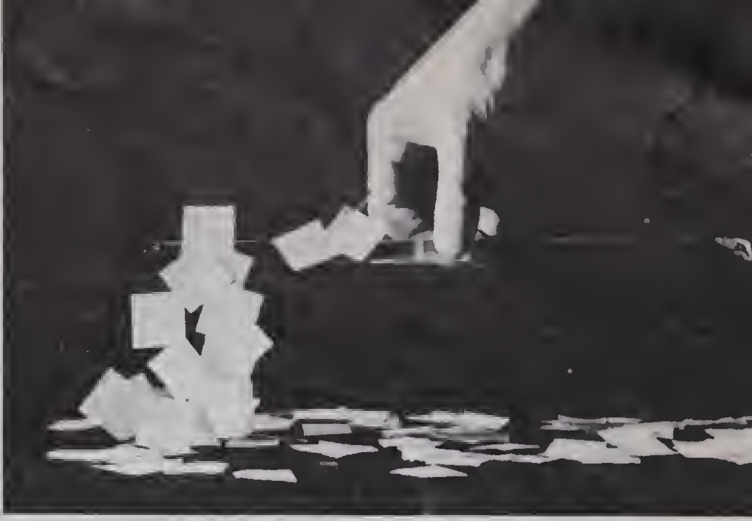


Figure 4–12 A rod charged by rubbing at one end will attract paper only at that end.

4–15 The electroscope detects electric charges. One device for showing that a metal is a good conductor of electrons is an electroscope (Fig. 4–13). Developed in 1787, it is the oldest of the electrical measuring instruments. If you touch the metal knob at the upper end with a charged rubber rod, electrons are transferred to the knob. Almost immediately the gold leaves at the lower end of the metal rod spread

Figure 4–13 Electroscopes, such as this one, are used to detect electric charges.

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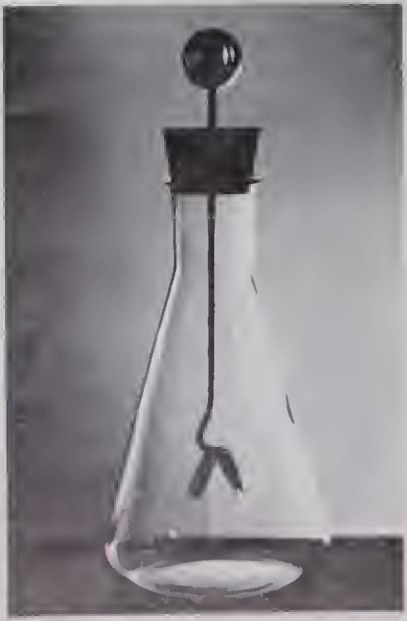


apart, showing that electrons have traveled down the rod. The repulsion of the electrons on one gold leaf for the electrons on the other leaf causes the spreading (Fig. 4–14). An electroscope can also be charged by induction, as shown in Fig. 4–15.

Once an electroscope has been charged in such a way that you know whether it has a positive or negative charge, you can then use it to test the *polarity* (negative or positive) of unknown charges, as shown in Fig. 4–16. The relative strengths of various charges can also be shown by the degree of deflection of the leaves when the charges are held at a fixed distance.

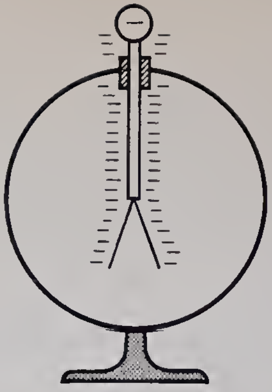


Figure 4–14 This electroscope has been touched by a negatively charged object. Electrons have been transferred to the electroscope by conduction, and the entire instrument bears a negative charge because the mutual repulsion of the electrons has caused them to spread out in the metal.

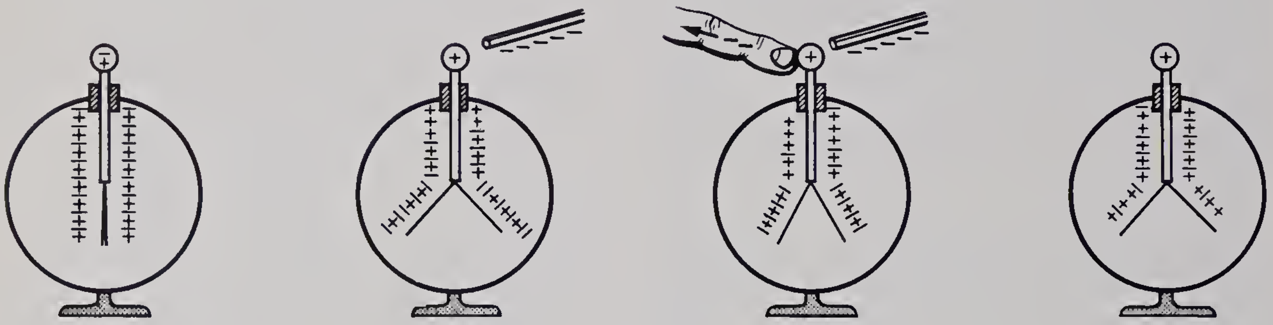


Figure 4–15 a. A neutral electroscope has equal numbers of positive and negative charges. **b.** When a negative rod is brought near, it drives electrons into the leaves, which become negative and deflect. The knob is positive. **c.** If you touch the knob, some electrons are repelled out through your hand. The top is less positive than before, and the leaves almost collapse. **d.** If you remove your hand and then the rod, the electroscope has a deficiency of electrons and is positively charged. The leaves fall as the electrons are redistributed, and then they rise again.

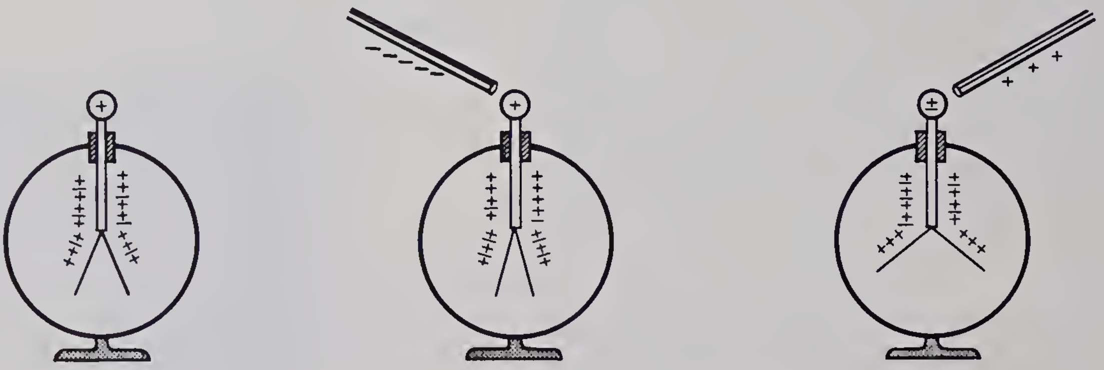


Figure 4–16 a. This electroscope has been charged positively. No other charged object is nearby. **b.** A nearby negative object drives some electrons away from the upper end of the electroscope and down into the leaves. Since the leaves are less strongly charged, they do not repel each other so much. **c.** The nearby positive object attracts some electrons up from the leaves, leaving them more positive than before. Since they now have a stronger charge, they repel each other with greater force.

Self Check

1. If a rubber rod is rubbed with wool or fur, the rod becomes negatively charged. What is the source of the charge?
2. If a glass rod is rubbed with silk, the rod becomes positively charged. How did the charge get there?
3. If you hung up a charged rubber rod so that it is free to swing, and brought a similarly charged rubber rod near it, what would you expect to happen?
4. If you hung up a charged rubber rod so that it is free to swing, and brought a charged glass rod near it, what would you expect to happen?
5. What is the law of electrostatic forces as illustrated by Questions 3 and 4?
6. Compare the electron, proton, and neutron with respect to charge and mass.
7. Who gave the present names to the two kinds of electric charge?
8. A negative charge of 0.001 C is built up on an electrostatic generator by friction. What happens while this charge is building?
9. State Coulomb's law in words and as an equation.
10. What is the name of the unit of electric charge in the mks system?
11. Compare electrostatic forces with gravitational forces.
12. Why is a normal atom neutral?
13. A negatively charged insulated rod is brought near a piece of thread that has no charge. What happens and why?
14. Compare the distribution of charge on two rods, one brass and one plastic, if each has been charged by conduction at one end and each is supported by a good insulator.
15. Why are metals better conductors of electricity than glass?
16. If a negatively charged rod is brought near the knob of a positively charged electroscope, what happens to the electroscope leaves? Why?

Problems

Ⓐ 1. Write the mass of an electron as a decimal (see p. 83).

Ⓑ 2. A small, negatively charged pith ball lying on a table is pulled up from the table by the force of attraction between it and another positively charged pith ball held 2 cm above it. If the ball weighs 0.1 g, what is the smallest possible charge on each of the two balls if both balls have the same charge?

Discussion Questions

1. At the time of Benjamin Franklin and for some time thereafter, there was considerable discussion about two rival electrical theories. One, held by Franklin, was that electricity was a single fluid; the other was that it was two fluids. Show that, in a way, both of these are partly right.
2. In what way is the law of conservation of charge more like the law of conservation of momentum than like the law of conservation of mass-energy?
3. If you touch the knob of a charged electroscope, the leaves fall. What does this tell you about the human body as a conductor?
4. Explain what happens if a positively charged rod touches the knob of a neutral electroscope.
5. A negatively charged rod is brought near a metal ball on an insulated stand. What kind of charge would you expect to find on the side of the ball near the rod? On the side away from the rod? Why?
6. What would happen to the charges in Question 5 if the rod were removed? What would happen if you touched the far side of the ball before the rod was removed and then took your finger away? What would then happen when you took the rod away from the metal ball?

The Nature of Atoms

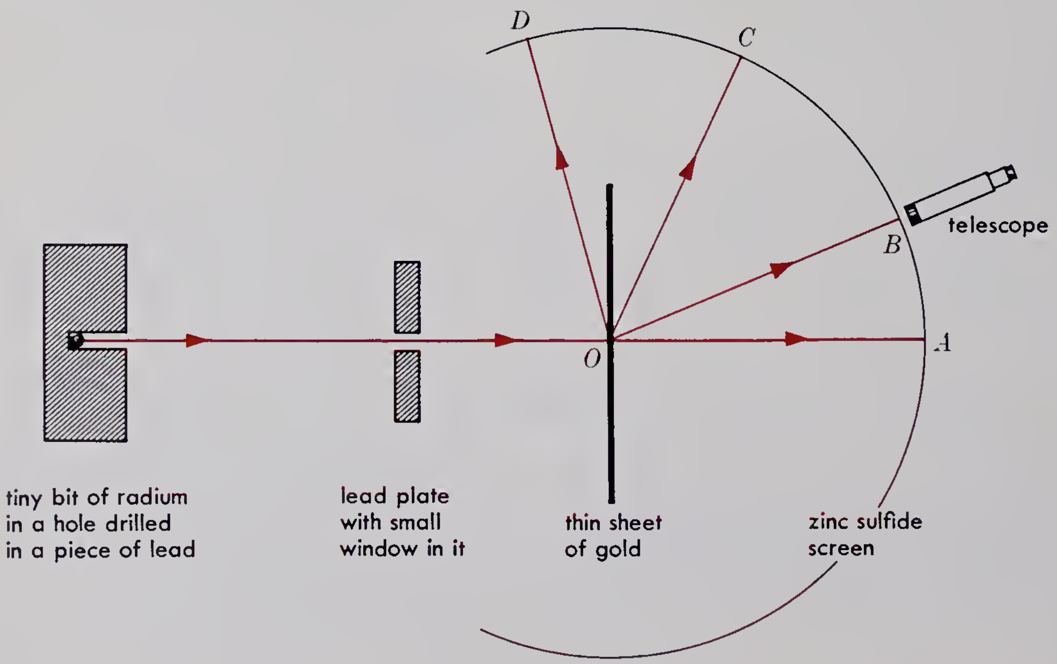
4–16 Rutherford discovers the nucleus. For many years scientists thought that atoms could not be broken down into anything smaller. Then, in 1897, J. J. Thomson, an English physicist, discovered the existence of electrons.

Electrons were found to be extremely tiny and to have a negative charge. But matter as a whole is neutral. Thomson therefore realized that if the electrons were part of an atom, there must be a positive charge in each atom, just enough to balance the electrons. No one knew much about this positive charge. Was it uniformly distributed in the atom, with electrons mixed throughout it? Thomson thought that this might be the case.

An exciting piece of detective work followed. Atoms, electrons, and protons are too small to be seen. But when a charged particle hits a screen coated with a chemical, zinc sulfide, it makes a tiny flash of light on the screen, telling just where it hit.

Scientists at the University of Manchester in England used these tiny flashes of light to investigate the interior of atoms. They planned to shoot charged particles through gold atoms to see whether the particles went straight through or had their paths bent. The charged particles came from radium and were known as alpha particles or α particles. To be sure the particles were all traveling in one direction when they hit the atoms being investigated, the scientists put the radium in a hole bored in a piece of lead, and then provided another piece of lead as a window frame to narrow the beam (Fig. 4–17). After this the alpha particles passed through a thin sheet of gold. Being positive, the alpha particles would be at-

Figure 4–17 Design of Rutherford's apparatus. Alpha particles shooting out from the radium can escape only horizontally. They pass through the sheet of gold and then hit the zinc sulfide screen, which glows each time it is struck. It is observed through the telescope, and the angle through which the particle has been deflected can be measured. Deflections which produce angles such as AOC and AOD can occur only if each atom has a nucleus.


D
C
telescope
B
A
O
tiny bit of radium in a hole drilled in a piece of lead
lead plate with small window in it
thin sheet of gold
zinc sulfide screen

tracted by the electrons and repelled by the positive charges in the atoms of gold.

Now if the positive and negative charges were well mixed together in the gold atoms, then the speeding alpha particles would be repelled and attracted nearly equally on all sides and either go straight through the gold or be only slightly scattered from the straight path. The result is shown in Fig. 4–17. Most of the scattering was slight, but there were a few large angles (angle *AOC*, for example), and sometimes the alpha particle even went backwards after striking the gold (angle *AOD*).

To explain how this could happen, Ernest Rutherford suggested that the positive charge might all be concentrated in a very small region, the **nucleus**, with the electrons at some distance. Then, if an alpha particle happened to get close to a nucleus, the great repulsion between the two positively charged objects — the nucleus and the alpha particle — would radically change the path of the alpha particle, giving it a large scattering angle. Of course, an alpha particle that passed halfway between two nuclei would not be deflected, but would go straight through.

In 1911 Rutherford determined mathematically (using Coulomb's law) the per cent of the alpha particles that should be scattered at various angles if his idea about the nucleus were correct. When the experiment was repeated, it was found that the scattering agreed with his prediction. Rutherford, therefore, concluded that an atom has a positively charged nucleus. Two years later, Niels Bohr, a student of Rutherford, showed that the electrons probably revolve about the nucleus.

The radius of the nucleus has been found to be only about one hundred-thousandth of the radius of the atom as a whole. Since the nucleus has most of the mass of the atom, it is very dense. It is so dense that 1 in^3 of the nuclear material would have a mass of four trillion tons!

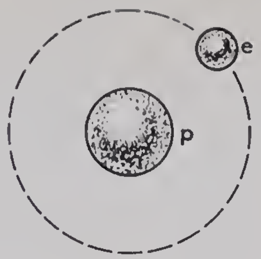


Figure 4–18 Model of a simple hydrogen atom. Its nucleus consists of 1 proton and 1 electron revolving around it. The radius of the orbit is 100,000 times the radius of the nucleus. Most of the mass is in the nucleus. The drawing is not to scale.

4–17 Electrons determine the chemical nature of elements. Whenever all the atoms in a substance are alike in the number of protons and electrons they have, the substance is an **element**. Oxygen, for example, is an element. Each of its atoms has 8 protons and 8 electrons. All the millions of different substances found on the earth are made of elements or combinations (compounds) of elements. About ninety elements have been found to occur naturally on the earth.

The lightest element is hydrogen. Its atom has only one electron. To balance the negative charge of this electron it has a nucleus with one positive charge (Fig. 4–18). A proton and a hydrogen nucleus are, therefore, the same thing.

The next heavier element is helium, the gas used in dirigibles and blimps. It has two electrons circling the nucleus. However, an atom of helium is approximately four times as heavy as a hydrogen atom. The hypothesis first proposed to account for the extra mass was that there were not two but four protons in the nucleus, with two of these protons neutralized by two electrons. Then in 1932 the neutron was discovered by J. Chadwick. According to present-day atomic theory, the helium nucleus contains 2 protons and 2 neutrons.

This is a good example of the way in which a theory grows and changes.

The **chemical nature** of an element is determined by the number and arrangement of the electrons circling around the nucleus of a neutral atom. By chemical nature is meant the way in which it will combine with other elements to make compounds. Helium, for example, is chemically inert. It forms no compounds at all. Hydrogen, on the other hand, is a very active element. It combines with many elements to make thousands of different compounds. It combines with oxygen so rapidly that it can cause explosions. This is why helium is preferred for lighter-than-air craft, although it is heavier than hydrogen.

4–18 Isotopes are nuclides with the same atomic number but different masses. While almost all hydrogen atoms have one proton and one electron, a few will have one or two neutrons in addition (Fig. 5–19). The three varieties of hydrogen all are chemically the same, because this factor is controlled by the single electron, but they do not have the same mass. Such forms of an element are called **isotopes**.

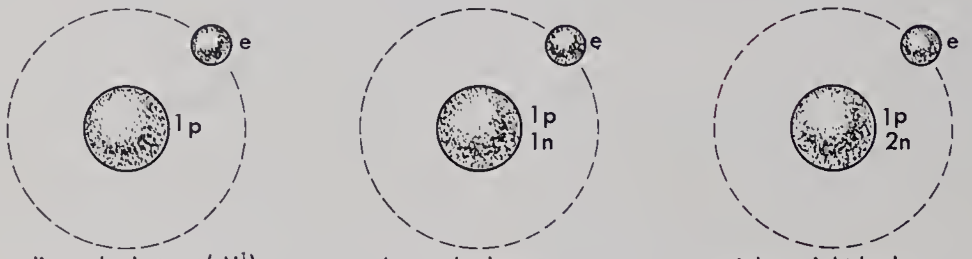
Every element has several isotopes, with the result that although there are only slightly more than a hundred different elements known, there are more than 1300 different varieties of atoms. Each of these varieties is called a **nuclide**. The scientific shorthand for each of the nuclides is shown under the drawings of Fig. 4–19. Take the symbol for tritium to see what each part means:

$$_{1}H^{3}$$

(mass number, A)
(symbol for hydrogen)
(atomic number, Z)

The **atomic number**, Z, is the number of protons in the nucleus and the number of

Figure 4–19

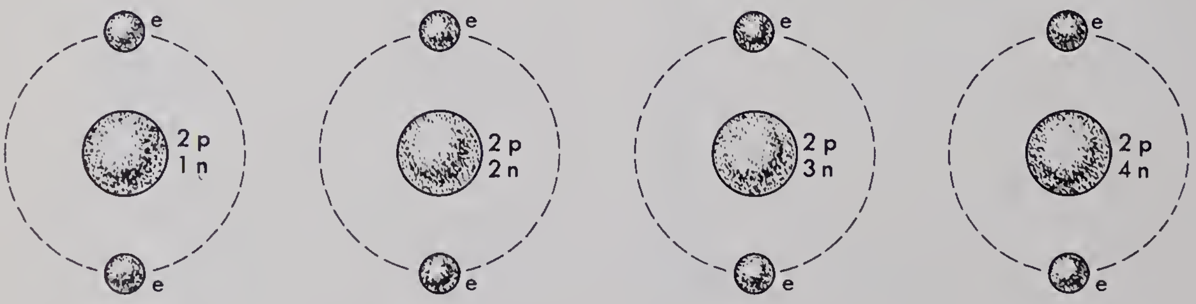


ordinary hydrogen ($_{1}H^{1}$)

heavy hydrogen or deuterium ($_{1}H^{2}$)

triple weight hydrogen or tritium ($_{1}H^{3}$)

Hydrogen has three isotopes. These three atoms are chemically alike because they all have 1 planetary electron and 1 proton, but they have different weights because of the different numbers of neutrons. 99.985% of all naturally occurring hydrogen atoms are of the first type. Nearly all of the rest is deuterium.



$_{2}He^{3}$ $_{2}He^{4}$ $_{2}He^{5}$ $_{2}He^{6}$

Helium has 4 isotopes. Natural helium is almost 100% $_{2}He^{4}$, although it contains a trace of $_{2}He^{3}$. $_{2}He^{5}$ and $_{2}He^{6}$ are produced as a result of nuclear experiments and have not been found in nature.

planetary electrons in a neutral atom. The **mass number**, A, is the total number of particles in the nucleus (protons plus neutrons). It is called the mass number because protons and neutrons weigh nearly the same and their sum accounts for most of the mass of an atom. Isotopes, then, can be defined as nuclides having the same atomic number but different mass numbers. Since hydrogen always has atomic number 1, tritium may also be written as H^3 with the 1 omitted.

Helium has four isotopes and you will notice that $_2He^3$ has the same mass number as tritium. Therefore, these two nuclides have almost the same mass. Their chemical behavior, however, is quite different.

Protons and neutrons are called **nucleons** because they are the particles found in the nucleus.

4–19 Atomic weights are based on carbon.

All known elements, both natural and artificial, are listed in Table 4–1. Since scientists may discover new elements of higher atomic number, you should be alert for news that might add to the list. Each element in the list has one more proton and one more electron than the one before. The number and arrangement of electrons account for the chemical behavior of the elements.

The term "chemical atomic weight" in the fourth column of Table 4–1 is misleading. Instead of weights, these are really masses, not in grams or kilograms, but in **atomic mass units (u)**. One atomic mass unit is $\frac{1}{12}$ of the mass of one atom of C^{12}. Notice that the chemical atomic weight of carbon is 12.011. This is because carbon in nature is 99% C^{12} and 1% C^{13}. Therefore when a chemist uses a naturally occurring sample of carbon for measuring the atomic weight, he finds that the average weight per atom is a bit more than 12. Chemical atomic weights are always determined for a naturally occurring sample, which is usually a mixture of isotopes.*

The atomic weight of any atom is approximately equal to the mass number of the most common isotope. Oxygen, for example, has an atomic weight of 15.999, indicating that the most common isotope is probably O^{16}. Since oxygen has atomic number 8, it has 8 protons in the nucleus, and O^{16} must also have 8 neutrons to make the mass number equal to 16. Similarly, the most common isotope of aluminum (atomic number 13, atomic weight 26.98) has 27 nucleons, 13 of which are protons. Therefore it has $27 - 13$, or 14 neutrons. See Fig. 4–20 on p. 95.

The atomic mass unit is also used to measure the **nuclidic mass**, the mass of a single nuclide. In metric units, $1\ \text{u} = 1.6603 \times 10^{-27}$ kg.

Long before electrons and protons and neutrons were discovered, chemists were able to measure atomic weights. When they noticed that for most of the elements the weights are very close to being whole numbers, they thought they might show that all larger atoms were made of collections of hydrogen atoms. When they came to chlorine, however, they gave up. The chemical atomic weight of chlorine is 35.453, just about halfway between two whole numbers. This does not look like a multiple of hydrogen. Now it appears that the old hypothesis was not so far off after all, for chlorine is a mixture of two isotopes, Cl^{35} (75.5 percent) and Cl^{37} (24.5 percent). Each atom of these isotopes is composed of 17 protons (or hydrogen nuclei), 17 electrons, and either 18 or 20 neutrons.

---

* Before 1962 physicists used $\frac{1}{16}$ of the mass of one atom of O^{16} as their atomic mass unit, while chemists used $\frac{1}{16}$ of the average mass per atom of a sample of naturally-occurring oxygen. Since oxygen in nature is a mixture of isotopes, the two units had a different size. The C^{12} unit has now been accepted by both groups of scientists, and is therefore called the *unified* atomic mass unit.

Table 4–1 LIST OF THE KNOWN ELEMENTS

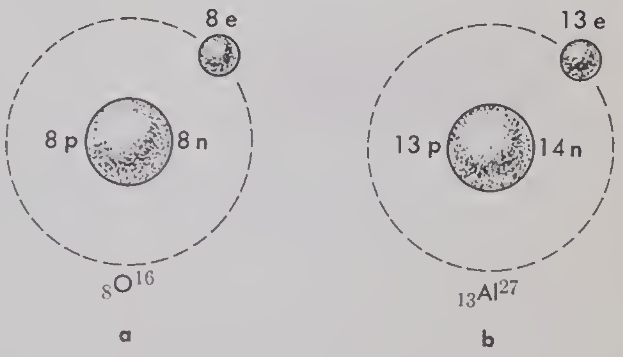
Element	*Symbol*	*Atomic Number (Z)*	*Chemical Atomic Weight (based on carbon 12)*
Hydrogen	H	1	1.008
Helium	He	2	4.003
Lithium	Li	3	6.939
Beryllium	Be	4	9.012
Boron	B	5	10.811
Carbon	C	6	12.011
Nitrogen	N	7	14.007
Oxygen	O	8	15.999
Fluorine	F	9	18.998
Neon	Ne	10	20.183
Sodium	Na	11	22.990
Magnesium	Mg	12	24.312
Aluminum	Al	13	26.982
Silicon	Si	14	28.086
Phosphorus	P	15	30.974
Sulfur	S	16	32.064
Chlorine	Cl	17	35.453
Argon	A	18	39.948
Potassium	K	19	39.102
Calcium	Ca	20	40.08
Scandium	Sc	21	44.956
Titanium	Ti	22	47.90
Vanadium	V	23	50.942
Chromium	Cr	24	51.996
Manganese	Mn	25	54.938
Iron	Fe	26	55.847
Cobalt	Co	27	58.933
Nickel	Ni	28	58.71
Copper	Cu	29	63.54
Zinc	Zn	30	65.37
Gallium	Ga	31	69.72
Germanium	Ge	32	72.59
Arsenic	As	33	74.922
Selenium	Se	34	78.96
Bromine	Br	35	79.909
Krypton	Kr	36	83.80
Rubidium	Rb	37	85.47
Strontium	Sr	38	87.62
Yttrium	Y	39	88.905
Zirconium	Zr	40	91.22
Niobium	Nb	41	92.906
Molybdenum	Mo	42	95.94
Technetium	Tc	43	[99]
Ruthenium	Ru	44	101.07
Rhodium	Rh	45	102.905
Palladium	Pd	46	106.4
Silver	Ag	47	107.870
Cadmium	Cd	48	112.40
Indium	In	49	114.82
Tin	Sn	50	118.69
Antimony	Sb	51	121.75
Tellurium	Te	52	127.60
Iodine	I	53	126.904
Xenon	Xe	54	131.30
Cesium	Cs	55	132.905
Barium	Ba	56	137.34
Lanthanum	La	57	138.91
Cerium	Ce	58	140.12
Praseodymium	Pr	59	140.907
Neodymium	Nd	60	144.24
Prometheum	Pm	61	[147]
Samarium	Sm	62	150.35
Europium	Eu	63	151.96
Gadolinium	Gd	64	157.25
Terbium	Tb	65	158.924
Dysprosium	Dy	66	162.50
Holmium	Ho	67	164.930
Erbium	Er	68	167.26
Thulium	Tm	69	168.934
Ytterbium	Yb	70	173.04
Lutetium	Lu	71	174.97
Hafnium	Hf	72	178.49

Element	Symbol	Atomic Number (Z)	Chemical Atomic Weight (based on carbon 12)
Tantalum	Ta	73	180.948
Tungsten	W	74	183.85
Rhenium	Re	75	186.2
Osmium	Os	76	190.2
Iridium	Ir	77	192.2
Platinum	Pt	78	195.09
Gold	Au	79	196.967
Mercury	Hg	80	200.59
Thallium	Tl	81	204.37
Lead	Pb	82	207.19
Bismuth	Bi	83	208.980
Polonium	Po	84	[210]
Astatine	At	85	[210]
Radon	Rn	86	[222]
Francium	Fr	87	[223]
Radium	Ra	88	[226]
Actinium	Ac	89	[227]
Thorium	Th	90	232.038
Protactinium	Pa	91	[231]
Uranium	U	92	238.03
Neptunium	Np	93	[237]
Plutonium	Pu	94	[242]
Americium	Am	95	[243]
Curium	Cm	96	[247]
Berkelium	Bk	97	[249]
Californium	Cf	98	[251]
Einsteinium	Es	99	[254]
Fermium	Fm	100	[253]
Mendelevium	Mv	101	[256]
Nobelium	No	102	[254]
Lawrencium	Lw	103	[257]

The numbers in brackets are the mass numbers of the most stable isotopes.

Figure 4–20 How to determine the structure of an atom.

1. Name of the element:	Oxygen	Aluminum
2. Find atomic weight of its most common isotope from Table 4–1.	15.999	26.982
3. Write mass number (A). This is usually the whole number closest to the atomic weight. This is the number of particles in the nucleus.	16	27
4. Write the atomic number (Z). This is the number of protons in the nucleus and the number of planetary electrons.	8	13
5. Subtract, $A - Z$. This gives the number of neutrons.	8	14
6. Draw a simplified diagram:		



Electron orbits are complex. Because of the complications involved in trying to picture electrons in their orbits, in these diagrams they are merely grouped together to show that they balance the positive charge of the nucleus.

4–20 Loss or gain of electrons produces ions. The aluminum atom shown in Fig. 4–20 is a neutral atom. It has 13 electrons to balance the positive charge of the 13 protons in the nucleus. Electrons, being on the outside of the atom, can sometimes be removed. If you could take away one or two electrons from the outside of an atom, the atom would have a net positive charge of one or two units. An atom that has a charge because it has lost or gained electrons is an **ion**. If the atom has lost electrons, it is a **positive ion**. Sometimes a neutral atom picks up an extra electron or electrons. In this case the atom becomes a **negative ion**. An electron which is unattached can also be called an ion. When you rub a plastic comb through your hair, you **ionize** both the comb and your hair. Atoms in the comb gain electrons and become negative ions. Atoms in your hair lose electrons and become positive ions.

Gases are easily ionized by fast-moving charged particles, which knock electrons out of the gas atoms as they strike them. Water vapor tends to condense on ions, forming droplets. This is why you can see the path of the electrons in the cloud chamber photograph of Fig. 4–3. As the electrons move rapidly through the supersaturated air, they ionize the gas, and droplets are formed on the ions. The electrons themselves are invisible, but it is possible to see where they have been and to measure their speeds. A similar kind of track is formed in a bubble chamber. Figure 4–21 on p. 97 shows several cloud and bubble chamber photographs.

Self Check

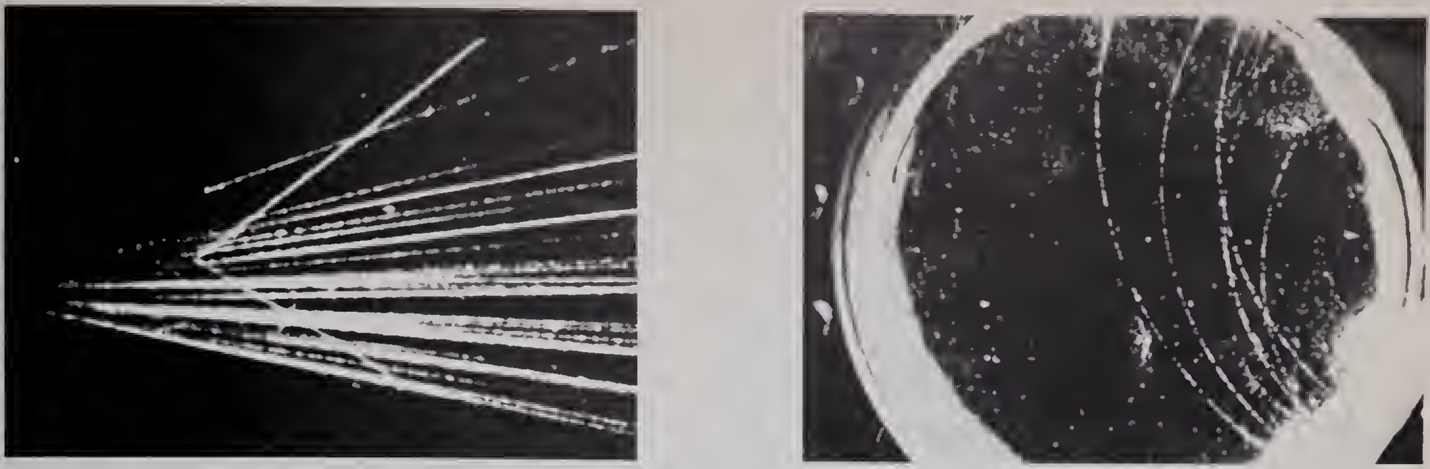
1. Describe the structure of an atom.
2. Describe the structure of an ordinary hydrogen nucleus.
3. Describe the structure of an ordinary helium nucleus.
4. What determines the chemical behavior of an element?

The symbol for oxygen is O, for nitrogen N, for carbon C. Questions 5–11 refer to the following nuclides: ${}_8O^{16}$; ${}_7N^{16}$; ${}_6C^{15}$; ${}_7N^{15}$; ${}_8O^{15}$; ${}_8O^{17}$.

5. Three of the nuclides are isotopes of each other. Which are they?
6. Which have the most neutrons, and how many do they have?
7. Which have the same number of protons as electrons?
8. Which have the same number of protons as neutrons?
9. Which have the most electrons, and how many do they have?
10. Which have the largest mass number, and what is the number?
11. Which have the smallest atomic number, and what is the number?
12. The chemical atomic weight of lithium is 6.939. What does this tell you about lithium?
13. What is the standard for comparison of chemical atomic weights and nuclidic masses?
14. What is an ion?
15. Why is the path of an electron in a cloud chamber visible when the electron itself is invisible?

Discussion Questions

1. The following nuclei have been discovered for helium: He^3, He^4, He^5, He^6. How many isotopes of helium are known?
2. Argon (A) has atomic number 18 and chemical weight 39.9. Potassium (K) has atomic number 19 and chemical atomic weight 39.1. How can the element with the higher atomic number have the lower atomic weight?

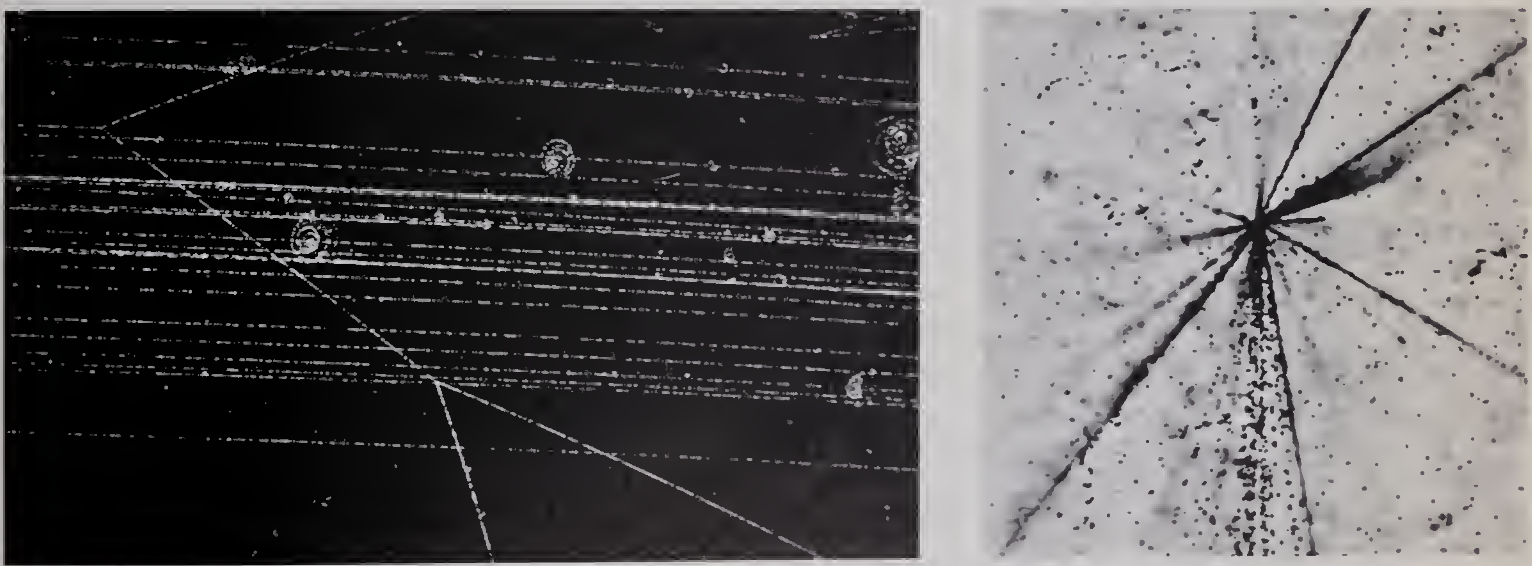


Courtesy of P. M. S. Blackett, published by permission of the Council of the Royal Society.

a. Tracks made by alpha particles in a cloud chamber. The paths are straighter and wider than the electron paths of Fig. 4–3. showing that alpha particles create more ions and are less readily deflected by collisions than electrons. The forked track was caused by the collision of an alpha particle with a helium nucleus. The two particles rebounded, obeying the laws of conservation of momentum and energy. From such tracks scientists draw conclusions about the masses and velocities of particles.

Courtesy of H. R. Crane, The University of Michigan.

b. Compare these electron tracks with Fig. 4–3, The fact that these are not being deflected first one way and then another as they collide with air molecules shows that they are going much faster. The tracks curve because the cloud chamber has been placed between the poles of a powerful magnet. If the particles had been charged positively instead of negatively, the tracks would have curved in the opposite direction. A magnetic field can therefore be used to identify the kind of charge on a particle.



Courtesy of Brookhaven National Laboratory.

c. High-speed protons crossed from left to right. One of them collided with a hydrogen atom, producing a forked path. The lower particle collided again, producing another fork. Put a ruler along the proton paths and note that they curve slightly downward in the magnetic field. You should be able to draw conclusions about the charge, mass, and speed of the particles that made the small spiral tracks. These tracks were made in a bubble chamber which was filled with hydrogen at its boiling point. Bubbles of hydrogen gas formed wherever moving particles ionized the liquid.

Courtesy of Dr. H. Yagoda, Air Force Cambridge Research Laboratories.

d. Moving ions in a photographic emulsion expose the chemicals, thus creating the tracks. Here a high-energy proton has scored a direct hit on a heavy nucleus in the emulsion. The nucleus has broken into a shower of other particles.

Figure 4–21 How scientists learn about invisible particles. (Also study the photograph and caption on page 72.)

Transmutation of Elements

4–21 The alchemists' dream of making gold was not realized. As the king watched, the alchemist stirred a concoction in his iron pot. Strange vapors arose, and unpleasant odors.

"See, sire, there is gold," said the alchemist, pouring the liquid from his ladle to reveal the gleam of yellow in the bottom.

The king, of course, was delighted. If his alchemist could change cheap lead into gold, he could become the most powerful king on earth. The alchemist, however, was a rogue who had fooled the king by putting small pieces of gold into his pot and then pouring over them a dark melted wax. When the wax hardened, it looked like the bottom of the pot. With much ceremony the alchemist had put in his ingredients, heated the pot, melted the wax, and fished out his gold.

The alchemist was forced to be a rogue to keep his job. However, he believed that some day he would find a true method to make gold from other metals. All matter, he thought, was made of four elements, earth, air, fire, and water, and his problem was to arrange the proper mixture of these four. While there was much magic, superstition, and dishonesty involved in alchemy, these scientists of the Middle Ages did discover and record many chemical facts. However, none of them succeeded in making gold from cheaper metals.

4–22 The dream comes true. Today, the ancient dream of the alchemist has come true, but it is hardly likely to make anyone's fortune. In a huge particle accelerator (Fig. 16–9 in Chapter 16) costing millions of dollars, a stream of protons is directed at a target made of a heavy element, bismuth. One of the results of this bombardment is that an isotope of lead is formed that spontaneously changes to gold. The process is very expensive, and the amount of gold made is extremely small.

In spite of this fact, the **artificial transmutation** (changing) of the elements is one of the most exciting developments of modern science. Although it has not produced gold in quantity, it has produced isotopes of various elements that are of great value in medicine, agriculture, industry, and national defense; and it has given man an entirely new source of energy.

4–23 Nuclear bombardment transmutes elements. As you have seen, the chief difference between one element and another is the number of protons in the nucleus, and the only difference among isotopes of the same element is the number of neutrons. If you wish to change one element into another, all you need do is to add or subtract protons, and if you wish to change the isotopes, all that is necessary is to manipulate the neutrons.

This is not as easy as it sounds, for the nucleus is very tightly bound together and does not easily accept newcomers or let out its occupants. The principal method used to change a nucleus artificially is to bombard it with small particles moving at high velocity. Table 4–2 on the opposite page lists particles often used for this purpose.

The apparatus used to speed up these particles for nuclear bombardment is called a **particle accelerator,** and there are many kinds. Cyclotrons, betatrons, Van de Graaff generators, and proton synchrotrons are a few of them. They can accelerate charged particles only. Neutrons are not accelerated in this manner because they have no charge.

Table 4–2 PARTICLES OFTEN USED FOR NUCLEAR BOMBARDMENT

(In this table, the mass of a proton is taken as 1, and the other masses are then compared with it.)

Particle	*Charge*	*Rest Mass*	*Comments*
Electron	—	0	Of course, the electron does have a mass, but compared with that of protons and neutrons, it is too small to consider, so it is given here as 0.
Neutron	0	1	Neutrons and protons have about the same mass, so both are listed as 1.
Proton	+	1	$_1H^1$ nucleus
Deuteron	+	2	$_1H^2$ (deuterium) nucleus
Triton	+	3	$_1H^3$ (tritium) nucleus
Alpha	++	4	$_2He^4$ nucleus
Photon	0	0	A tiny packet of energy found in light, x-rays, rays from radium, etc.

4–24 Other particles are produced during nuclear transmutations. When a nucleus is hit by one of the bombarding particles, it may capture the particle or it may break up in some way.

Study the photographs in Fig. 4–21. As a result of evidence such as this, scientists now find themselves confronted with more than 30 fundamental particles. This has not changed the idea that matter is primarily made up of electrons, protons, and neutrons. These three are the "old reliables" of the universe. The other particles are created for brief moments when the electrons, protons, and neutrons collide. Table 4–3 on the next page lists some of the particles now known.

4–25 Does a universe of antimatter exist? Some scientists have wondered whether there might be, somewhere off in space, a universe of **antimatter** in which atoms have negative nuclei made of antiprotons and antineutrons, surrounded by swarms of positrons. If there is such a universe, a collision between it and our universe would produce a tremendous explosion, after which there would be nothing left but energy. Astronomers and physicists are actually searching for evidence in space that such a thing might be happening. They look for places where more energy is pouring out than can be accounted for in any other way.

Self Check

1. What dream of the alchemists has become possible today?
2. Why would the modern transmutation of lead into gold give no satisfaction to the alchemists?
3. What is the principal method used to transmute elements?

Table 4–3 FUNDAMENTAL PARTICLES

(In this table, the mass of an electron is taken as 1, and the other masses are then compared with it.)

Particle	*Rest Mass*	*Charge*	*Comments*
Electron	1	−1	These three are the fundamental building blocks of our universe.
Proton	1836	+1	
Neutron	1839	0	
Positron	1	+1	Each of these particles is the exact opposite of the corresponding particle in the first list. Each will combine with its opposite, with the result that they destroy each other. There is no mass left then, but energy equal to mc^2 is produced, where m is the sum of the two disappearing masses. These are the fundamental particles of "antimatter."
Antiproton	1836	−1	
Antineutron	1839	0	
Muons, Mesons, and Baryons	207 to over 3000	+1, 0, −1	There are several dozens of these. In some cases they occur in groups of three, having nearly the same weight and three different charges. Many of them are formed when a nucleus is broken up by a bombardment. Some of the mesons are called "nuclear glue" because they seem to help to explain why the positive charges in a nucleus can be held together in spite of the tremendous electrostatic repulsion that must exist between like charges close together. It is possible that some of them may be combinations of others. These particles change rapidly into other particles and into energy. They have average lives ranging from two millionths of a second to less than ten trillionths.
Neutrinos	0	0	Formed when a neutron changes into a proton and an electron, and in some other reactions. There are 2 kinds of neutrinos and 2 kinds of antineutrinos.
Antineutrino	0	0	
Photon	0	0	Packet of energy.

4. What are some fields in which new isotopes have shown their value?
5. What is the purpose of a particle accelerator?
6. Which particle cannot be accelerated by a particle accelerator?
7. What is changed when an element undergoes transmutation?
8. What are the antiparticles corresponding to the proton, electron, and neutron?
9. What happens when a particle meets its antiparticle?

Discussion Questions

1. How can you tell that the electron on p. 72 was slowing down? What made it slow down?
2. How does the electron-positron pair on p. 72 illustrate the law of conservation of charge?
3. What conclusions do you draw about the particles that caused the spiral tracks in Fig. 4–21c?

Transmutation Produces Energy

4–26 The whole is not equal to the sum of its parts. Here is some rather interesting arithmetic. Consider the helium atom:

1 helium atom ($_2He^4$)
= 2 protons + 2 electrons + 2 neutrons

Now 1 proton + 1 electron is the same as a hydrogen atom. Therefore:

1 helium atom
= 2 hydrogen atoms + 2 neutrons

This equation says that a helium atom is composed of 2 hydrogen atoms plus 2 neutrons. Then the masses of the various parts should equal the mass of a helium atom. The masses are given in Table 4–4.

Now comes the arithmetic. Using the figures from Table 4–4:

$$\begin{array}{rl} 2.01566\text{ u} & = \text{mass of 2 hydrogen atoms} \\ +\ \underline{2.01734\text{ u}} & = \text{mass of 2 neutrons} \\ 4.03300\text{ u} & = \text{mass of 2 hydrogen atoms} \\ & \quad + \text{2 neutrons} \end{array}$$

But the mass of a helium atom is 4.00260 u, which is less than 4.03300 u. The helium atom has a smaller mass, although both are composed of 2 protons, 2 electrons and 2 neutrons. The difference between these two numbers is 0.03040 u, which is 0.75 percent (¾ of 1 percent) of the mass of the helium atom.

You might think that this discrepancy could be due to a slight mistake in the measurement of the masses, but this is not the case. The measurements have an error less than 0.001 percent. Therefore, another way must be found to account for the difference.

Table 4–4 REST MASSES OF SMALL PARTICLES

These masses are given in (unified) atomic mass units (u). One u is 1/12 of the mass of an atom of C^{12}. It is equal to 1.66×10^{-24} g.

Particle	*Rest Mass*
Electron	0.00055
Hydrogen (H^1) atom	1.00783
Neutron	1.00867
Helium (He^4) atom	4.00260

4–27 Mass becomes energy. Apparently if you could put together protons and neutrons and electrons to construct helium atoms, a small fraction of the mass would disappear. Where would it go? The Einstein relativity theory gives the answer. It would become energy. Therefore, if helium atoms were made out of hydrogen atoms and neutrons, energy would be produced equal to Δmc^2, where Δm is the loss in mass. This is what is probably going on in the sun and stars to give them their enormous energy. The process is complicated, but the end result is the production of helium from hydrogen, some of the hydrogen protons being changed into neutrons.

What happens with other atoms? Lithium 7 has a mass of 7.01601 u and atomic number 3. Therefore, it has 3 protons, 3 electrons, and 4 neutrons, the equivalent of 3 hydrogen atoms plus 4 neutrons.

3.02349 u = mass of 3 hydrogen atoms
+ 4.03468 u = mass of 4 neutrons
7.05817 u = mass of 3 hydrogen atoms + 4 neutrons
− 7.01601 u = mass of lithium 7 atom
0.04216 u = discrepancy in the mass

If you repeat this arithmetic for every isotope of every element, you find that the mass of the atom is always smaller than the sum of the masses of the particles of which it is made. Here are some examples:

Atom	*Discrepancy in the mass*
$_1H^2$	0.0024 u
$_2He^4$	0.0304 u
$_3Li^7$	0.0422 u
$_6C^{12}$	0.0990 u
$_8O^{16}$	0.1371 u
$_{26}Fe^{56}$	0.529 u
$_{92}U^{238}$	1.94 u

If you could find a way to build heavier atoms out of the very light ones, you would always get energy in addition to the new atoms. When Einstein predicted this back in 1905, no one knew how to do it. Today light atoms have been combined into heavier ones in the hydrogen bomb.

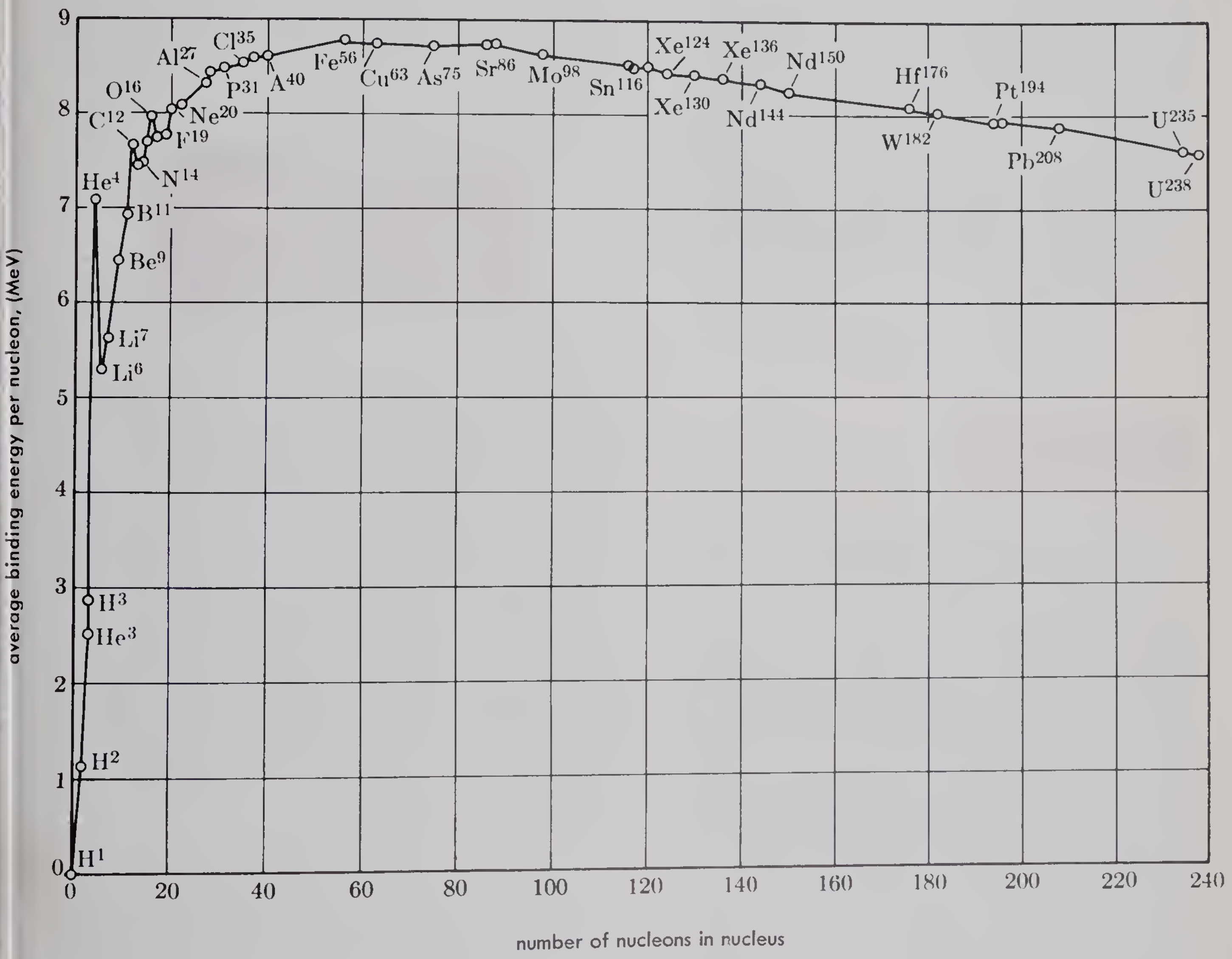
The discrepancy in the mass of an atom is called **binding energy** because it is the energy produced by the binding together of neutrons and hydrogen atoms to form heavier atoms. It is also the energy that must be supplied to break an atom into neutrons and hydrogen atoms. In this case you might like to call it the "unbinding energy." The binding energy can be measured in atomic mass units, as was done here, or it can be converted into joules by using the equation $E = \Delta mc^2$, where Δm is the mass discrepancy.

Notice that the mass discrepancy or binding energy becomes greater as the mass of the atom becomes greater. In the list above, it is greatest for U^{238} and least for deuterium (H^2). This is reasonable, for the larger the number of particles packed into a nucleus, the greater the mass loss is likely to be. In order to even out the effect so that a better comparison can be made between one atom and another, it is customary to divide the total binding energy by the mass number, or number of nucleons. This then tells the binding energy per unit of mass of the substance. In Fig. 4–22 you see how the binding energy per nucleon changes as the mass of the nucleus increases. The combining of atoms of light elements to form heavier atoms, with a resultant production of energy, is called **nuclear fusion**.

4–28 Light elements may be made to undergo fusion. The calculations using hydrogen and helium show that energy would be produced if hydrogen atoms could be combined to make helium. Even though only three quarters of one percent of the mass is lost in the process, the energy produced would be enormous. Earlier in this chapter (p. 78) the amount of energy produced if 1 g of matter were converted to energy was found to be enough to supply 10,000 homes with electric power for a year. If 1 g of hydrogen could be made into helium, the mass loss would be ¾ percent of 1 g, or 0.0075 g, a weight so small you could not feel it. The energy produced could make electricity for ¾ percent of 10,000 homes, or 75 homes for a year (or for 1 home for 75 years).

It is believed that the hydrogen-into-helium process is the source of the heat and light of the sun and stars. One problem in getting this reaction to take place is that protons (hydrogen nuclei) repel each other with such force that it is very difficult to get them close enough together to fuse into helium nuclei. Only when they are moving fast enough can this be done, and to make them go fast enough they must be heated to a very high temperature, as is the case in the sun and stars. If man wishes to use the fusion of light elements for power production, he must solve the temperature problem. This is now the subject of a great deal of research.

Figure 4–22 Graph of binding energy per nucleon vs. mass number.



From Holton and Roller, FOUNDATIONS OF MODERN PHYSICAL SCIENCE, 1958, Addison-Wesley, Reading, Mass.

4–29 Heavy elements may undergo fission. Examine the graph of Fig. 4–22. You will notice that the binding energy per nucleon increases very rapidly at the start, reaches a maximum along near the middle, and then decreases.

Suppose you started with hydrogen atoms to make helium atoms. You have already seen that there is much energy given off. Now you use more hydrogen atoms, to make heavier and heavier nuclei. The binding energy curve rises, showing that more energy is given off. Then when you get to iron you reach the top of the curve.

Now note that if you make atoms heavier than iron, the curve slopes down. This means that instead of giving off energy the nucleus is taking in energy. The heavier the nucleus gets from here on, the more energy it stores up. Therefore, if you could break a very heavy nucleus, uranium, for example, down to middleweight atoms, you should be able to obtain an enormous amount of energy. This process is known as **nuclear fission**

Self Check

1. How many hydrogen atoms and how many neutrons would it take to make one atom of sodium 23 (${}_{11}Na^{23}$)?
2. If you added together the masses of the hydrogen atoms and neutrons needed to make one atom of sodium 23, how would the sum compare with the mass of an atom of sodium 23?
3. What is the name given to the difference in the masses described in Question 2?
4. What becomes of the mass lost when heavy atoms are made from light ones?
5. What is nuclear fission?
6. What is nuclear fusion?
7. Which of these is the source of energy in the sun and stars?

Problems

B 1. If $1\ \text{u} = 1.66 \times 10^{-24}$ g, how much energy in joules is produced by the disappearance of 1 u of mass?

2. Compute the binding energy in u for C^{12} and U^{238} given the following atomic masses in u: C^{12}, 12.0000; U^{238}, 238.05.

3. Determine the binding energy in joules for C^{12} and U^{238}.

Discussion Question

Does the binding energy per nucleon increase in a regular way with increase in mass number? (See Fig. 4–22.)

Chapter Summary

The mass of an object is not a constant, but increases as its speed increases. The increase is measurable only at speeds approaching that of light in a vacuum. The speed of light in a vacuum is probably the speed limit for a moving mass. As an object speeds up, its increase in kinetic energy is directly proportional to its increase in mass. Therefore, mass is considered a stored form of energy. The rest mass and relativistic mass of an object are its masses when motionless and when moving, respectively. The kinetic energy of a moving object is given by the equation: $\Delta E = \Delta mc^2$. The law of conservation of mass-energy has supplanted the separate laws of conservation of matter and conservation of energy.

All matter is electrical in nature. There are two kinds of electric charge, positive and negative. Like charges repel, unlike charges attract each other with a force that follows Coulomb's law. The primary particles out of which matter is made are protons, electrons, and neutrons. The existence of charged objects can be explained in terms of these particles. In all cases of charge production, charge is conserved. The unit of electric charge is the coulomb. Electrostatic forces among atomic particles are tremendous compared with gravitational forces among these same particles.

Atoms are composed of electrons, protons, and neutrons. All of the atoms of an element have the same number of protons and electrons, but may differ in number of neutrons. The charging of objects by conduction or induction and the behavior of insulators and conductors can be explained in terms of the behavior of the electrons in atoms.

Atoms have a positively charged nucleus composed of protons and neutrons and surrounded by planetary electrons. The number and arrangement of electrons in a neutral atom determines its chemical behavior. An element may have several isotopes. A nuclide is described in terms of its atomic number and mass number. Nuclidic masses and chemical atomic weights are related to the mass number. Ions are charged atoms, charged groups of atoms, or unattached electrons.

Transmutation of nuclei is possible. Particle accelerators are used to speed up particles that cause transmutation when they bombard nuclei. Other particles formed during transmutation include positrons, mesons, antiprotons, antineutrons, and various others.

For all nuclides except H^1, the sum of the masses of the hydrogen atoms and neutrons of which they are made is less than the atomic mass. The discrepancy in mass represents an energy loss called the binding energy and is equal to the energy required to break up the atom. Fusion of lighter elements into heavier ones results in conversion of part of the mass to energy. Fission of heavy elements into middle-weight ones also results in conversion of part of the mass to energy.

Vocabulary

rest mass (*p. 74*)
relativistic mass (*p. 74*)
energy equivalent (*p. 77*)
conservation of mass-energy (*p. 78*)
cloud chamber (*pp. 80, 96*)
static charge (*p. 81*)
electrostatic force (*p. 81*)
electron (*p. 83*)
proton (*p. 83*)
neutron (*p. 83*)
conservation of charge (*pp. 83, 84*)
coulomb (*p. 85*)
atom (*p. 86*)
charging by induction (*p. 87*)
charging by conduction (*p. 87*)
insulator (*p. 87*)
free electron (*p. 87*)
conductor (*p. 87*)
electroscope (*p. 87*)
polarity (*p. 88*)
alpha particle (*p. 90*)
nucleus (*p. 91*)
element (*p. 91*)
chemical nature (*p. 92*)
isotope (*p. 92*)
nuclide (*p. 92*)
atomic number (*p. 92*)
mass number (*p. 93*)
nucleons (*p. 93*)
chemical atomic weight (*p. 93*)
atomic mass unit (*p. 93*)
nuclidic mass (*p. 93*)
ion, ionize (*p. 96*)
bubble chamber (*pp. 96, 97*)
photographic emulsion (*p. 97*)
particle accelerator (*p. 98*)
transmutation (*p. 98*)
deuterium, deuteron (*p. 99*)
tritium, triton (*p. 99*)
antimatter (*p. 99*)
antiproton (*p. 99*)
antineutron (*p. 99*)
positron (*p. 100*)
meson (*p. 100*)
binding energy (*p. 102*)
nuclear fusion (*p. 102*)
nuclear fission (*p. 104*)

Problems

B 1. What is the relativistic mass at a speed of exactly 0.6 *c* of an object with a rest mass of exactly 1 kg?

2. The example on p. 78 showed that the conversion of 1 g of mass into energy yields 2.5×10^7 kWh. Suppose that you reverse the process and use electrical energy to produce mass. Your expense is very low, only 1 cent per kWh. What would it cost to produce 1 g of mass? Consult the catalog of chemicals in your science room to see whether there are any that are worth producing at this rate.

3. How many lithium 7 atoms would have to be made from hydrogen and neutrons in order to produce 1 kWh of energy? What would be their mass?

Discussion Questions

1. If you dropped a penny from the top of a skyscraper, its impact on the head of a pedestrian might be enough to kill him. Is this because of the mass increase in the penny?
2. The idea that mass increases with increase in speed is part of Einstein's theory of relativity. Notice that word, *relativity*. If you were in a spaceship traveling away from the earth at half the speed of light, your mass should be increased by 15 percent according to the Einstein equation. How would the change affect your observation of yourself?
3. One of the major problems of modern physics is the question of what holds the nucleus together. What do you know about the nucleus that would lead you to think that it ought not to stay together?
4. Explain the attraction of a neutral piece of paper to a positively charged rod.
5. A hollow metal ball is charged negatively by conduction. What kind of charge would you expect to find on the inside surface of the ball? Why?
6. Why do physicists prefer to give atomic masses in atomic mass units rather than in grams or kilograms?

Work on Your Own

1. Look up H. A. Lorentz in the encyclopedia and see how his contributions to physics fitted in with those of Einstein.
2. Here are four books about Einstein and his work that you might enjoy reading:
   Lincoln Barnett, *The Universe and Dr. Einstein*, Wm. Sloane Associates, 1948. (This is also published in paperback, Mentor Book No. 71.)
   Martin Gardner, *Relativity for the Millions*, Macmillan Co., 1962.
   George Gamow, *Mr. Tompkins in Wonderland*, Cambridge University Press, 1939.
   Antonina Wallentin, *The Drama of Albert Einstein*, Doubleday and Co., 1954.
3. Books that have sections on Einstein's relativity theory and on modern alchemy are:
   Albert Einstein, and Leopold Infeld, *The Evolution of Physics*, Simon and Schuster, Inc., 1938, 1942.
   George Gamow, *One, Two, Three, Infinity*, Mentor Book No. 97, 1954.
   George Gamow, *Matter, Earth, and Sky*, Prentice-Hall, 1958.
4. For material on the history of our knowledge of electric charge, read "Electricity from the Greeks to Coulomb" by Roller and Roller in *Harvard Case Histories in Experimental Science*, Vol. 2, J. B. Conant, Ed., Harvard University Press, 1957.
5. Look up the contributions to understanding of the atom that were made by J. J. Thomson, Ernest Rutherford, and J. Chadwick.
6. Your school can get a free Chart of the Nuclides, listing all the isotopes of the atoms, by writing to General Electric Company, Public and Employee Relations Services, Schenectady 5, New York. A more complete and also more complicated Trilinear Chart of Nuclides is available from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D.C. at moderate cost.

PHYSICS HALL OF FAME

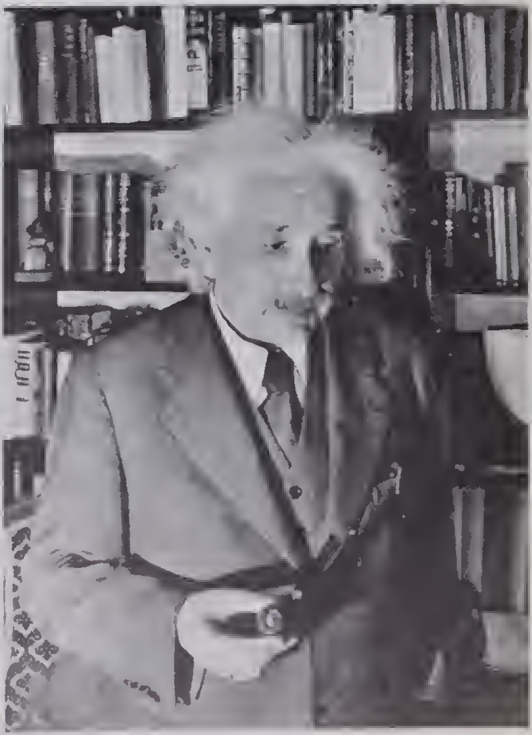
Albert Einstein · 1879–1955

Albert Einstein was only twenty-six years old when he published two papers that greatly contributed to the twentieth-century revolution in physics and technology. One of the papers, an explanation of the photoelectric effect, helped to establish the quantum theory by showing that light may act in some ways like a stream of particles. The photoelectric effect is now widely utilized in such devices as "electric eyes," sound motion pictures, and television. Einstein's other paper of 1905 described the special theory of relativity. The now famous equation $E = mc^2$, which led eventually to the development of nuclear energy, was part of this paper.

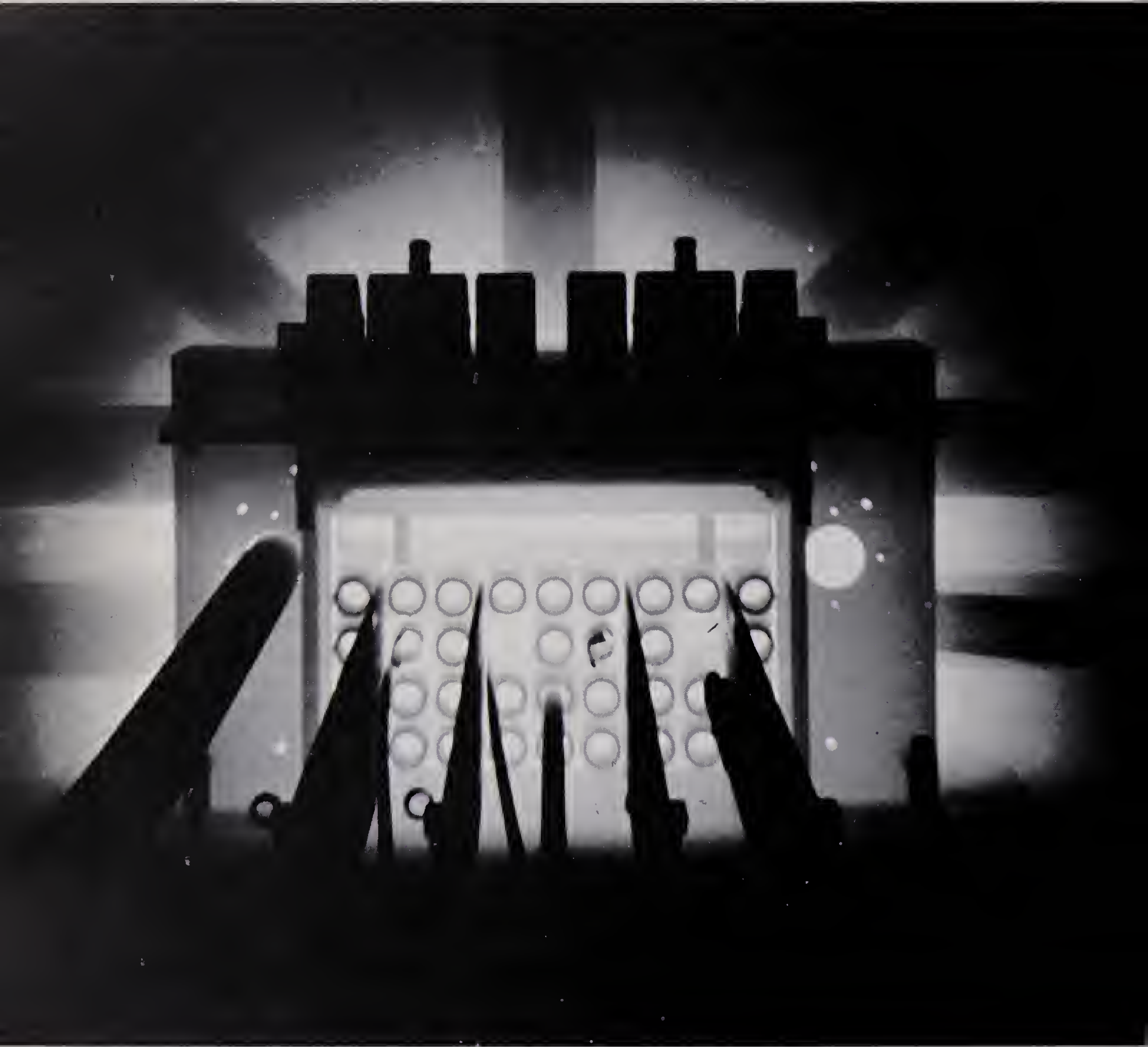
Einstein's general theory of relativity was proposed in 1915. It expanded Newton's ideas of gravitation by relating gravitational forces to the effects of the curvature of space. The theory has been widely accepted because many of its conclusions have been confirmed by observation.

In 1933, when Adolph Hitler became Chancellor of Germany, Einstein — who was of Jewish parentage — was deprived of both his German citizenship and the professorship he then held at the University of Berlin. Einstein had been visiting the United States shortly before that and decided to return. He was made Professor of Mathematics at the Institute for Advanced Study in Princeton, New Jersey, where he worked until his death. His last theory was an attempt to deal with electric, magnetic, and gravitational fields in one unified theory. Neither Einstein himself nor any other physicist has thought of a way to test this theory, however; and it has thus been neither accepted nor rejected as yet.

The contribution Einstein made to science was remarkable, but he is equally admired for his qualities as a human being. It is characteristic of his humanity that he would agree to write his autobiography only because, as he put it, "it is a good thing to show those who are striving alongside of us, how one's own striving appears . . . in retrospect."



CHAPTER 5



Courtesy of Los Alamos Scientific Laboratory, University of California.

This is a view looking down into a tank of heavy water surrounding a nuclear reactor. Nuclear particles shoot out of the reactor with such speed that they move faster in the water than the speed of light in water (not faster than the speed of light in a vacuum). As a result, a glow is produced in the water, known as Cerenkov radiation.

Nuclear Energy

If you have a wrist watch or a clock with a luminous dial, look at it with a hand lens some night in a dark room, and after your eyes have become adjusted to the dark, you will see flickering flashes of light all over the dial. If you observe the dial with a microscope, you will see individual flashes, each caused by the transmutation of a single nucleus of radium.* Radium is therefore a source of nuclear energy, but the energy is produced in such small amounts that it is not useful for power. Furthermore, the rate at which radium nuclei produce the energy cannot be controlled.

Natural radioactivity — like that of radium — was discovered in the 1890's. Not until 1939 did scientists discover a way to control nuclear energy. This chapter is a history of the discoveries that have led to nuclear-powered ships, nuclear electric generators, and nuclear weapons, to cancer-destroying nuclides, to radioactive tracers, and to plasmas as shown on the opposite page.

Natural Radioactivity

5–1 Uranium produces radiation. Professor Henri Becquerel was interested in fluorescent substances, chemicals that glow when light shines on them (such as those on many road signs today). The year was 1896. A German scientist, W. K. Röntgen, had recently discovered a mysterious radiation that he called x-rays. Becquerel thought that his fluorescent chemicals might give off x-rays when they were exposed to sunlight.

In a dark room he took a photographic plate and wrapped it in heavy black paper so that ordinary light could not affect it. On the package Becquerel placed one of his fluorescent substances, a compound of uranium. As soon as the sun shone, he would put the package where the light would fall on the compound. Then if the sunlight caused the compound to produce x-rays, he would know it because x-rays can go through black paper and would therefore affect the plate. The sun, however, did not shine. For several days he waited. Still no sun. Finally, fearing that some stray light might have gotten in, he developed his plate. Imagine his amazement when he found the exact outline of the

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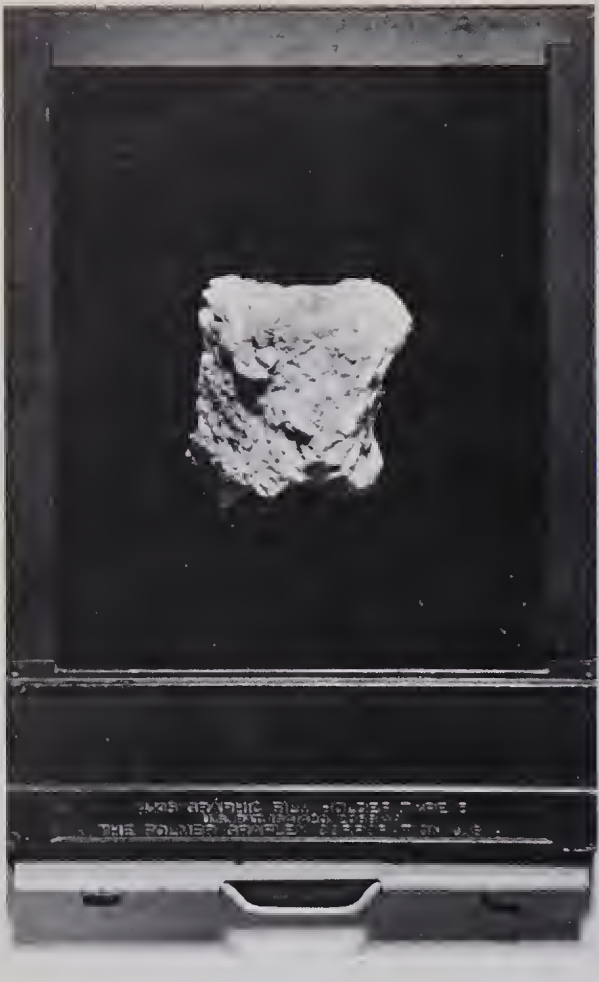
* If you try this, you must either use a photographic dark room or do it at night. It will take 10 minutes or more for your eyes to become sufficiently sensitive to see the flashes. It may be necessary to remove the crystal from the watch in order to bring the numerals or hands into focus. Focus the microscope before turning out the light.



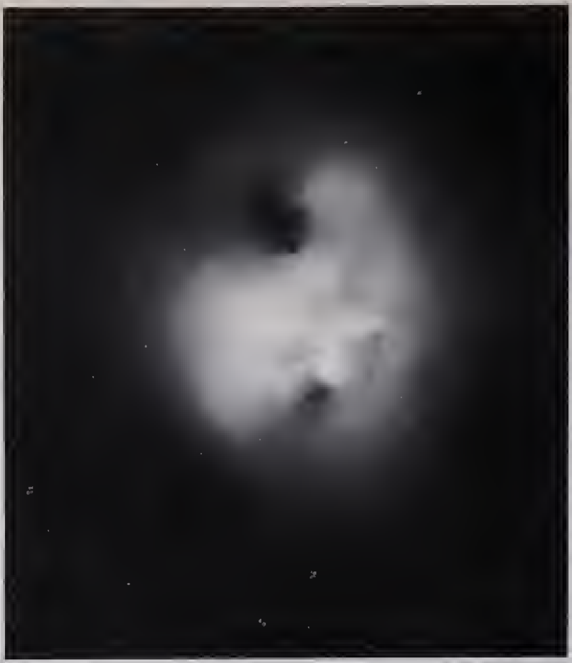


Figure 5–1 The photographic plate on the left cannot be exposed by ordinary light because it is inside a plate holder. The object on top of the plate is a lump of ore containing uranium. The picture above shows that the rays from the ore have passed through the paper and exposed the plate.

compound on the plate (Fig. 5–1)! Even without sunlight, this substance was sending out rays that could pass through black paper.

He tried the experiment again, this time completely in the dark, so that no kind of light could reach the compound. Again the plate had an image. He used other compounds. Whenever there was uranium in the compound, the blackening occurred; without uranium there was no reaction. Even when the uranium compound was not a fluorescent one, the photographic plate was affected. He tested at high temperatures and at low ones. The results were the same.

An entirely unknown kind of radiation was coming from uranium. It happened without being started, and it could not be stopped or even slowed. If it were due to a chemical change in which the atoms of a molecule were rearranged, then different uranium compounds should behave differently, but they did not. This energy must have something to do with the nature of uranium atoms themselves.

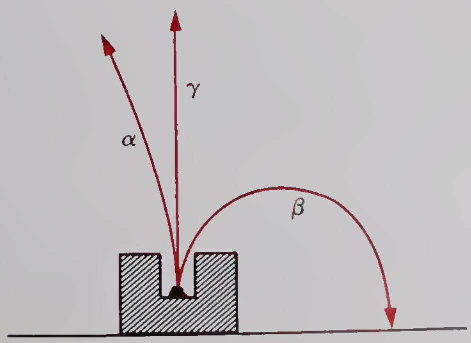
5–2 The Curies discover radium. Pierre and Marie Curie knew Becquerel and were interested in his discovery. Marie studied a number of ores of uranium and found that one of them, pitchblende, seemed to be sending out more radiation than could be accounted for by the uranium it contained. This started the Curies on one of the most backbreaking scientific investigations of all time. They decided to separate all the substances they could find in a ton of pitchblende. For months they carried pitchblende and concentrated the ray-producing part, trying to find what was sending out rays even stronger than those from uranium.

Finally they announced the discovery of two new elements. The first they named polonium, for Marie's native country, Poland. The second they named radium. And how much radium did they find in their ton of ore? Less than a hundredth of an ounce! Yet this tiny bit of radium was more powerful than the 600 pounds of uranium in the ore! It was Marie Curie who gave the name **radioactivity** to the action of these substances.

5–3 Radioactive substances produce three kinds of radiation. Many people began to study the rays given off by radioactive substances. Three kinds of rays were detected; they were named with the first three letters of the Greek alphabet: *alpha* (α), *beta* (β), and *gamma* (γ). Alpha rays could be stopped by an ordinary sheet of paper or a few inches of air. Beta rays would go through many feet of air and thin sheets of metal. Gamma rays could be stopped by 1½ miles of air or a foot of lead.

In addition, the effect of a magnet on the path of these rays coming from radium was studied (Fig. 5–2). Alpha rays were found to bend in one direction and beta rays in another. Gamma rays were not deflected. Scientists already knew that a magnetic field causes the path of a moving charged particle to curve, the direction of the curve depending on whether the charge is positive or negative. Therefore this and other experiments led to the conclusion that **alpha rays** were positive helium nuclei, **beta rays** were electrons, and **gamma rays** were very much like x-rays but more penetrating. Alpha and beta particles come out of a nucleus with a great deal of kinetic energy, and gamma rays carry away energy too. A **radioactive element** is one in which the nucleus disintegrates spontaneously, giving off various kinds of radiation.

Figure 5–2 This diagram shows charged particles from radium being deflected by a magnetic field. Alpha particles are deflected in one direction, showing that they are positive; beta particles, in the other direction, showing that they are negative. The curvature of the paths shows that alpha particles are much heavier. Gamma rays are undeflected, showing that they have no charge.



5–4 Radioactive decay produces new elements. When a nucleus shoots out an alpha particle or an electron, the nucleus changes into that of a new element. The most common isotope of uranium, $_{92}U^{238}$, is a good example. The composition of the uranium is:

Number of nucleons	238
Minus the number of protons ...	− 92
Number of neutrons	146

When uranium decays, it gives off an alpha particle, which is a helium nucleus, containing 2 protons and 2 neutrons. The 90 protons and 144 neutrons left behind become the nucleus of a new element. The early investigators called it uranium X_1 (UX_1). To find out what it is, look for atomic number 90 in the table of elements on p. 95. It is one of the isotopes of thorium.

This reaction can be written as a nuclear equation:

$$_{92}U^{238} \rightarrow {}_{90}Th^{234} + {}_{2}He^{4} + \text{energy}$$

An arrow is used here, as in equations for chemical reactions, instead of an equals sign to show that the U^{238} changes into the other elements. When this happens there is a tiny loss of mass, which is converted into energy, partly gamma radiation and partly the kinetic energy of the alpha particle ($_2He^4$). Notice in this equation that the mass numbers at the top balance ($238 = 234 + 4$)

and the numbers at the bottom also balance ($92 = 90 + 2$). Whenever you write nuclear reactions, be sure to check the arithmetic involved. Since this is a nuclear reaction, the numbers refer to protons and neutrons only; ignore planetary electrons.

Thorium 234 is also radioactive. When it decays, it shoots off a beta particle, an electron, not one of its planetary electrons, but one from the nucleus. How can this happen, if the nucleus contains only protons and neutrons? Apparently a neutron changes into a proton and an electron. The electron is shot off and the proton stays in the nucleus. The thorium nucleus has 90 protons. After the electron escapes there are 91 protons. The new element is protactinium. One neutron has changed to a proton and an electron, so there are 143 neutrons left in the new nucleus. The mass number (protons plus neutrons) remains the same. The nuclear equation is:

$$_{90}\mathrm{Th}^{234} \rightarrow {}_{91}\mathrm{Pa}^{234} + {}_{-1}\mathrm{e}^{0}$$

An electron is written as $_{-1}e^0$. The 0 indicates that it has no significant mass. Only protons and neutrons contribute to the mass number of a nucleus. The -1 is the charge of the electron. Remember that this electron came from the nucleus and not from the planetary electrons. Notice that the numbers balance: $234 = 234 + 0$ and $90 = 91 + (-1)$.

The protactinium also decays, forming a new **radioisotope** (radioactive isotope) of uranium, and the reactions continue until finally the nucleus becomes a **stable** (nonradioactive) isotope of lead. It is rather ironic that the natural transmutation of the elements should end up with lead, the element the alchemists hoped to change into gold.

5–5 Half-life is a measure of radioactive decay. Imagine a pond full of minnows, 160,000 of them. You have a boat that drags a large net through the pond. In one trip around the pond, your net picks up half the minnows. Now there are 80,000 left, but they swim in all directions so that they fill in the gaps left by the minnows you caught and are well distributed over the pond by the time you have emptied the net. You start on the second trip around. Your net is just as good as before, so it will still catch half of the minnows in the pond. Since there are fewer minnows, on the second trip you catch 40,000, leaving 40,000 in the pond. Again the minnows spread out into the spaces left. If you continue making trips, here is what happens:

Originally there were	160,000 minnows
At end of first trip there are	80,000
At end of second trip there are	40,000
At end of third trip there are	20,000
At end of fourth trip there are	10,000
At end of fifth trip there are	5,000

If it takes you 20 minutes to make the trip, then every 20 minutes half of the minnows disappear from the pond.

The decay of a radioactive element follows this kind of behavior. In a certain length of time, known as the **half-life**, one half of the atoms of the element form new atoms. The half-life of uranium 238, for example, is 4.5×10^9 years; it is a very long-lived isotope. Four and a half billion years from now, half of the uranium 238 now on the earth will have decayed to thorium 234. Thorium 234, on the other hand, has a half-life of about 24 days (Fig. 5–3). Some half-lives are extremely short. Polonium 214, one of the elements formed by the decay of uranium 238 into lead, has a half-life of 0.00016 seconds. No way of controlling the half-life of a radioisotope has been found. Changes in temperature or chemical composition have no effect on it.

5–6 Radioisotopes can be dangerous. The rays from uranium, radium, and other radioisotopes can be very dangerous. They

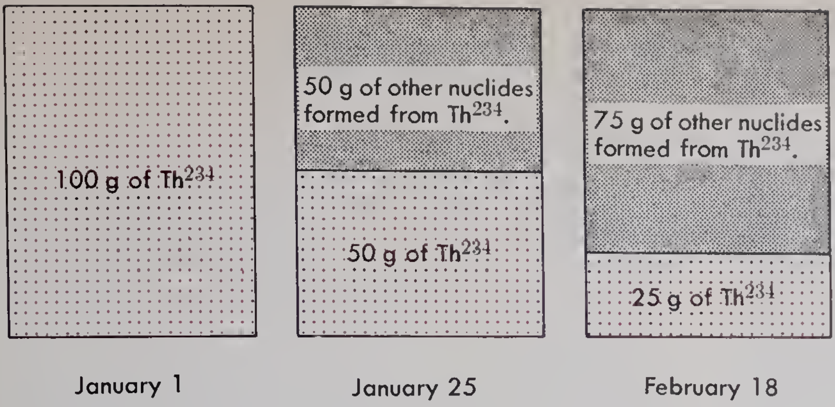

100 g of Th234
50 g of other nuclides formed from Th234.
50 g of Th234
75 g of other nuclides formed from Th234.
25 g of Th234
January 1
January 25
February 18

Figure 5–3 The decay of thorium 234. The half-life of Th^{234} is 24 days. If you had 100 g of Th^{234} on January 1, you would have 50 g 24 days later (January 25), and only 25 g after 24 more days (February 18).

can kill living cells, causing bad burns. They can destroy the proper functioning of cells and turn them into cancer cells. They can change the genes, which control heredity. The descendants of a person who is exposed to radiation, therefore, may possess organic defects. These facts were not known to the early investigators, and many of them died of cancer.

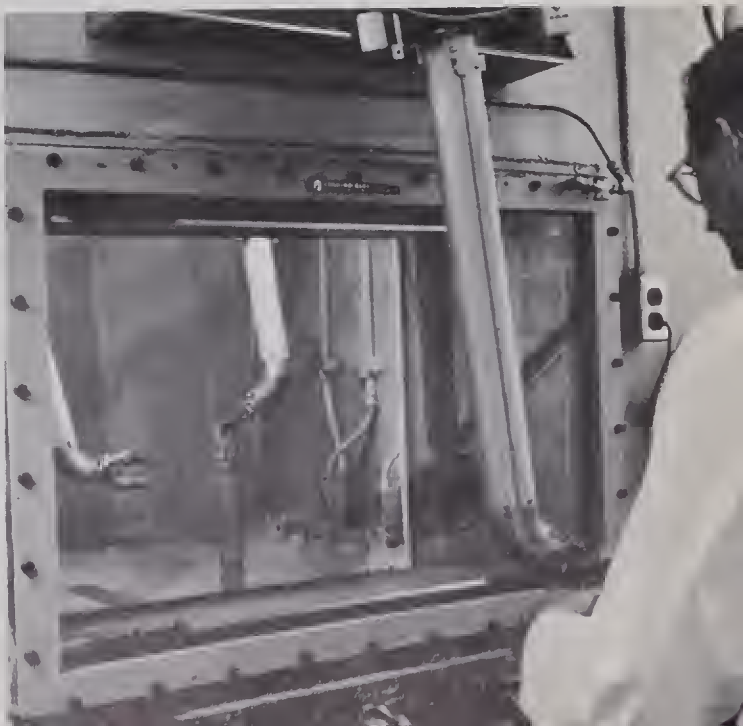
Today a person who handles radioactive substances takes many precautions. He does not pick up a highly active sample of uranium or radium in his fingers or carry it in his pocket. He stores it inside a metal container, usually lead, that will absorb the radiations. He handles the material at a distance (Fig. 5–4). He uses instruments that tell him how much radioactivity there is in a sample, so that he will know what precautions to take. One of these instruments is a Geiger-Müller counter (G-M counter or Geiger counter). Many Civil Defense units have small, portable counters that indicate on a dial the intensity of radioactivity.

5–7 Radioisotopes are extremely useful. Although radioactive rays can cause cancer, they have been used to cure it too. If the rays are directed on a cancer, they will kill the cells, and if the doctor judges the dose exactly, they may kill all of the cancer cells, thus curing the patient. Even if the dose is not quite great enough, the size of the cancer will be reduced and the life of the patient prolonged. Radium is frequently used for this. Of course the doctor must also be careful to center the rays on the cancerous tissues so that they do not damage healthy cells.

Uranium 238, 235, and 234, which are the naturally occurring forms, decay very slowly. U^{238} decays to U^{234}, and finally to Pb^{206}. U^{235} decays to Pb^{207}. For this reason, a rock containing uranium also contains these lead isotopes. They are not the common lead isotopes (Pb^{208}). The longer the uranium has been in the rocks, the higher is the percentage of these special isotopes of lead present. After determining the percentage of each isotope in a rock and knowing their half-lives, a scientist can calculate how long it has been since the uranium in the rock first started to decay. By analyzing uranium ores in rocks and meteorites, scientists have found that the oldest are about four and a half billion years old. They conclude that the earth is at least that old.

Another radioactive substance has made it possible to date the remains of ancient

Figure 5–4 Highly radioactive substances must be handled by mechanical hands such as these. The window is three feet thick.



civilizations. The common form of carbon is C^{12}, a stable isotope. However, the carbon dioxide of the atmosphere contains a tiny trace of a radioisotope of carbon, C^{14}. When plants take in carbon dioxide to make food, a small fraction of it is radioactive C^{14}. Animals eat the plants and get their share of radioactive carbon. This continues as long as the plants and animals live. However, as soon as the organism dies, no more C^{14} is absorbed. C^{14} has a half-life of 5770 years. A scientist can take a charred bit of wood from the fire of a primitive man, or a bit of bone, or a fragment from a roof beam of an ancient temple, and by comparing the percentage of C^{14} present with the percentage of C^{12}, he can determine when the tree was cut or when the animal died.

Self Check

1. Who discovered radioactivity?
2. What element did he find was radioactive?
3. Name the two people who soon afterward discovered two more radioactive elements.
4. What elements did they discover?

Answer Questions 5–9 with *alpha, beta,* or *gamma.*

5. Which radiation is the most penetrating?
6. Which radiation is composed of electrons?
7. Which radiation is composed of helium nuclei?
8. Which radiation(s) can be made to travel in a curved path when a magnet is brought near?
9. Which radiation(s) come from the nucleus of an atom?
10. ${}_{92}U^{235}$ decays by shooting off an alpha particle. Give the atomic number and mass number of the element formed.
11. ${}_{88}Ra^{228}$ decays by shooting off a beta particle. Give the atomic number and mass number of the element formed.
12. What happens to one neutron in the nucleus of an element that shoots off a beta particle?
13. What symbol is used for an electron in nuclear equations?
14. The half-life of one isotope of radium is about 1600 years. If a gram of radium were sealed up in a container, in how many years would it be reduced to 0.25 g?
15. Describe some of the precautions that must be taken in handling radioactive substances.
16. What are three harmful biological results from careless handling of radioactive substances?
17. What are two useful results that can be obtained with naturally radioactive substances?

Problems

(Consult the table of elements on p. 94 in doing these problems.)

Ⓐ **1.** Protactinium 234 gives off an electron. Then the next element in the series gives off an alpha particle, and the next one after that also gives off an alpha particle, becoming radium 226. Write the nuclear equations.

2. Radium 226 decays to lead 206 with the following particles being given off in order: (a) alpha; (b) alpha; (c) alpha; (d) beta; (e) beta; (f) alpha; (g) beta; (h) beta; (i) alpha. Write the nuclear equations.

3. C^{14} decays by giving off an electron. What nuclide is formed? Is this the common isotope of carbon?

4. Ba^{142} has a half-life of 6 minutes. If you started with 100 g, how much would be left at the end of half an hour?

Discussion Questions

1. Which would you expect to be more radioactive, a gram of radioactive substance with a short half-life or a gram of one with a long half-life? Why?
2. Some elements decay by giving off a beta particle from the nucleus. How does this illustrate the law of conservation of charge?

Artificial Radioactivity

5–8 The new rays help in the discovery of nuclides. After the discovery of radioactivity, nuclei, and isotopes, many scientists of the early 1900's were as excited as a man who loves to hunt might be if he found himself in an unexplored wilderness with all of the newest hunting equipment. The strange animals in their unexplored wilderness were all sorts of strange nuclides. For bullets they had the alpha, beta, and gamma rays from radium and uranium. They shot them into the nucleus and set loose the nuclides. To know when they had bagged their game, the nuclidehunters at first used electroscopes and zinc-sulfide screens (see Fig. 4–17) that glowed when the particles hit them. Then other devices were invented: G-M counters, cloud chambers, new kinds of counters, and, most recently, bubble chambers and spark chambers.

Alpha particles were the favorite bullets. They were heavier than the beta particles and more effective in smashing a nucleus. Rutherford, in 1919, was the first to change a nucleus. He shot alpha particles at nitrogen atoms and found that protons (hydrogen nuclei) were produced. To find out what else was happening, write the equation:

$$_2\mathrm{He}^4 + {}_7\mathrm{N}^{14} \rightarrow {}_Z\mathrm{X}^A + {}_1\mathrm{H}^1$$

Since a proton is a hydrogen nucleus, it is written as $_1\mathrm{H}^1$. X stands for the unknown nuclide with atomic number Z and mass number *A*. Remembering that the numbers must balance in these equations, you can figure out what the unknown nuclide must be. Take the numbers at the top first:

$$4 + 14 = A + 1$$

The mass number *A* must be 17 for the equation to balance. Now consider the lower numbers:

$$2 + 7 = Z + 1$$

The atomic number Z must be 8. The element with atomic number 8 is oxygen. Therefore the equation is:

$$_2\mathrm{He}^4 + {}_7\mathrm{N}^{14} \rightarrow {}_8\mathrm{O}^{17} + {}_1\mathrm{H}^1$$

This is not the usual isotope of oxygen but a naturally occurring stable isotope. Sometimes this equation is written:

$$_2\mathrm{He}^4 + {}_7\mathrm{N}^{14} \rightarrow ({}_9\mathrm{F}^{18}) \rightarrow {}_8\mathrm{O}^{17} + {}_1\mathrm{H}^1$$

This shows that for a fraction of a second the alpha particle and the N^{14} combine to make a fluorine nucleus, which then decays.

The energy in a beam of gamma rays will also break up a nucleus.

$$_4\mathrm{Be}^9 + \gamma \rightarrow {}_3\mathrm{Li}^8 + {}_1\mathrm{H}^1$$

The gamma ray has neither charge nor mass, so no numbers are used with it.

5–9 Chadwick discovers the neutron. Several scientists obtained an interesting result when they bombarded beryllium with alpha particles. Very penetrating rays were produced. They were not affected by a magnet so they could not be charged particles. At first it was thought they might be gamma rays. Then Irene Curie (a daughter of Marie and Pierre), and her husband, F. Joliot, directed the rays at a block of paraffin, a compound containing hydrogen. Protons (hydrogen nuclei) were knocked out of the paraffin.

Here the laws of conservation of energy and momentum had to be considered. The protons coming from the paraffin had so much energy and momentum that whatever was hitting them could not possibly be gamma rays. J. Chadwick, an English scientist, read about the experiment of the Joliot-

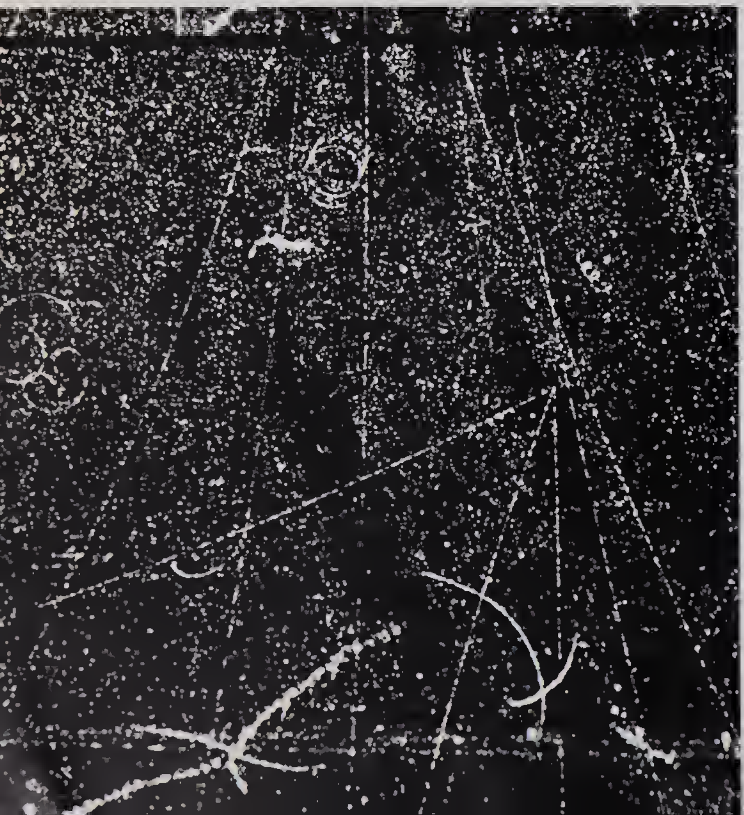
Curies. He investigated further and announced in 1932 that the energy and momentum problems would be solved correctly if the rays from beryllium consisted of neutral particles weighing about the same as protons. Thus the neutron was discovered. The Nobel Prize in Physics was awarded to Chadwick in 1935 for this discovery. What happens when beryllium is bombarded by an alpha particle is this:

$$_4\mathrm{Be}^9 + {}_2\mathrm{He}^4 \rightarrow {}_6\mathrm{C}^{12} + {}_0\mathrm{n}^1$$

The symbol for the neutron is $_0n^1$ to show that it has no charge and a mass of 1.

This mysterious particle cannot be detected in the usual way. It leaves no tracks in a cloud chamber because it passes through atoms easily, producing very few ions. It does not make a zinc-sulfide screen glow. It does not set off a G-M counter. But if it hits a nucleus directly, it can cause the nucleus to release charged particles that will leave tracks in a cloud chamber (Fig. 5–5). Furthermore, a neutron is more likely to hit a nucleus than is a charged particle of the same energy, which may be deflected by the planetary electrons if it is negative and by the nucleus if it is positive.

Figure 5–5 Very energetic protons, mesons, and neutrons entered this cloud chamber at the top. The neutrons made no tracks because they have no charge. The three-pronged track at the right was formed when a neutron struck a hydrogen atom. From the curvature of the three tracks in the magnetic field it is possible to conclude that the track straight down was formed by a proton and the others were formed by pi mesons.



5–10 The Joliot-Curies make an artificially radioactive isotope. Irene Curie and F. Joliot soon discovered that when aluminum is bombarded with alpha particles, it behaves like beryllium, giving off neutrons. The equation is:

$$_{13}\mathrm{Al}^{27} + {}_2\mathrm{He}^4 \rightarrow {}_{15}\mathrm{P}^{30} + {}_0\mathrm{n}^1$$

With both beryllium and aluminum, neutrons were given off only as long as the alpha particles kept coming. When the source of alpha particles was taken away, the neutrons stopped appearing. Since neutrons had already been discovered, the fact that they could also be obtained from aluminum was interesting, but not exciting.

But now the Joliot-Curies made a discovery that was exciting. After they took the source of the alpha particles away, they tested the aluminum with a G-M counter. It recorded a count. Two and a half minutes later, the count was half as great. In another two and a half minutes, the count was again one half as great. The fact that the G-M counter reacted showed that a radioactive element was present. Up until now, the only radioactive elements known were the heavy ones like radium and uranium. When the scientists bombarded aluminum with alpha particles, they had caused a change that produced a new radioactive element, a lightweight one, with a half-life of 2.5 minutes. This was the first man-made radioactive isotope.

The new radioactive substance that they had created was phosphorus 30. This decays by emitting a positron, which is formed by a proton changing into a neutron and a positron.

$$_{15}P^{30} \rightarrow {}_{14}Si^{30} + {}_{+1}e^{0}$$

The positron (see Table 4–3, p. 100) has the same mass as the electron, but a positive charge, as shown by the sign at the bottom.

The Joliot-Curies received the Nobel Prize in Chemistry in 1935 for being the first to make an artificially radioactive isotope.

5–11 The great nuclide hunt continues. The end is not in sight and may never be. After having used rays from radium, uranium, and other radioactive elements, scientists began to invent particle accelerators to make alpha particles, protons, and electrons go faster and faster before being used as bullets to break up the nucleus. They found that when they smashed some nuclei with these fast particles, they got streams of neutrons. They used the neutrons to smash other nuclei. Accelerated deuterons (H^2 nuclei) and tritons (H^3 nuclei) are also used as bullets. Every year the list of new nuclides, usually radioactive ones, grows.

Why do the scientists continue the nuclide hunt? There are two main reasons. First, each of these new discoveries adds to man's understanding of the nature of the universe. Every time a nucleus is broken up in a new way, the scientist learns a little bit more about what a nucleus really is. The second reason is that many radioisotopes have turned out to be useful in industry, medicine, and other fields.

5–12 Artificially radioactive isotopes treat disease. The thyroid gland in the neck uses iodine to manufacture a hormone that helps oxidize food. If a person has a cancer in this gland, one method of treatment is to have him drink a carefully measured dose of a radioactive iodine compound. The iodine is carried by the blood to the thyroid gland where it is captured. The cancer is thus exposed to the rays from the radioactive iodine. The isotope has a short half-life (about 8 days), so if the dose is small, the radioactivity will die out before any damage to the person can be done.

A few years ago an eight-year old girl began to have spells in which she sat and stared blankly, or acted strangely. The doctors thought she might have a brain tumor, but were not sure. Inside the bony skull, it is hard to locate such a growth. What could they do? They knew that brain tumors absorb arsenic. They knew also that there was a radioisotope of arsenic with a short half-life. They injected a tiny amount of this isotope into a vein and tracked down its location with radiation detectors. Back and forth moved the counters over the child's head. In a short time the doctors knew that the patient had a tumor and they knew just where it was. They operated and removed it. The little girl recovered completely.

Sometimes a patient with cancer is put in the path of the beam of particles from one of the big accelerators. The beams acts like the rays from radium to destroy the cancer.

5–13 Radioisotopes have many other uses. Zinc is one of the elements required by plants. To find out just what part of a plant uses zinc, an agricultural scientist puts a compound containing a radioisotope of zinc in the water given to the plant. Then he places the various parts of the plant on a photographic film. The radioactive zinc takes its own picture. The use of radioisotopes in this kind of research has added considerably to the knowledge of how living things grow.

Kerosene, aviation gasoline, ordinary gasoline, and other oils are shipped in pipe lines thousands of miles long. Suppose that a shipment of aviation gasoline is being followed in the line by a shipment of kerosene. At the right time it is important to switch the flow of liquid from the gasoline to the kerosene storage tanks. How can the men at the receiving end of the line know when to do this? At the starting end, a small amount of a radioactive compound is put in the line between the shipments. At the receiving end, a G-M counter placed some distance before the switching valves indicates just when the radioactive compound passes by. Almost immediately the switch is made, because there must be no kerosene in the aviation gasoline. A little gasoline in the kerosene will do no harm, however. The isotope used has a short half-life and is practically all gone by the time the kerosene is sold.

These are only a few examples of the many uses of radioisotopes. If you read the science articles in the daily newspapers or science magazines, you will discover many more.

Self Check

1. What were the three "bullets" originally used to break up the nuclei of atoms?
2. Name three ways in which particles produced by a breaking nucleus can be identified.
3. What is the symbol for a proton in a nuclear equation?
4. What two conservation laws helped in the discovery of the neutron?
5. Who discovered the neutron?
6. What is the symbol for a neutron in a nuclear equation?
7. How is a neutron detected?
8. What is meant by an artificially radioactive isotope?
9. What is the symbol for a positron in a nuclear equation?
10. Why do scientists continue to search for new nuclides?
11. Give one example of a medical use of radioisotopes or accelerated particles.
12. Give one example of a nonmedical use of radioisotopes.

Problems

In the problems that follow, find the nuclide formed. Consult the table of elements on pp. 94–95 for atomic numbers.

A 1. S^{32} bombarded with alpha particles emits a proton.

2. B^{11} bombarded with protons emits an alpha particle.

3. C^{12} bombarded with gamma rays emits an alpha particle.

4. Be^9 bombarded with protons emits a deuteron.

5. Ag^{107} absorbs a neutron and then emits an electron.

6. Li^6 bombarded with deuterons emits an alpha particle.

7. Li^6 bombarded with neutrons emits an alpha particle.

8. Al^{26} is radioactive and decays, emitting a positron.

9. C^{12} bombarded with a proton gives off a gamma ray.

B 10. Nuclear physicists have a shorthand way of writing nuclear equations. $Be^9(\alpha, n)C^{12}$ means that a beryllium 9 nucleus bombarded by an alpha particle emitted a neutron and was converted into a carbon 12 nucleus. This is the equation that is written in the long form on p. 116. Rewrite the equations of Problems 1–9 in shorthand form, using α (alpha), γ (gamma), p (proton), d (deuteron), n (neutron), β (electron), and β^+ (positron).

Discussion Questions

1. When a neutron is converted into a proton plus an electron, does the process take in energy or give it off? Consult Table 4–4.
2. Does the conversion of a proton into a neutron plus a positron take in energy or give it off?

Cosmic Rays

At the meeting of the American Association for the Advancement of Science in December, 1931, there was considerable excitement. Present were two giants of American physics, Robert A. Millikan and Arthur H. Compton. They were the only living Nobel Prize winners in physics in the United States. Millikan had been the first to measure accurately the charge of an electron. Compton had made the amazing discovery that x-rays can make electrons rebound when they hit them, just as if they were being hit by a stream of particles.

These two men had been studying the mysterious rays called cosmic rays, and they had come up with different conclusions. Millikan said they were probably something like gamma rays and x-rays, but with even shorter wave lengths. Compton said they were particles.

5–14 Electroscopes seemed to be malfunctioning. Cosmic rays were discovered because nuclear scientists were having trouble with their electroscopes. After they had charged them and the leaves were nicely deflected, they slowly lost their charge. What was the trouble? If the leaves went down suddenly, a scientist would assume that he had accidentally brushed against the knob, for the human body is a good conductor and removes extra electrons from a negative electroscope and conducts electrons to a positive electroscope. If it was a damp day, the scientist expected the electroscope to lose its charge to the many ionized water vapor molecules in the air. But even on dry days the leaves slowly dropped.

The electroscopes were being used to compare the activities of various radioactive materials. Rays from these substances ionize air molecules by knocking off some of the outer electrons. Therefore if a radioisotope is brought near a charged electroscope, the leaves drop as the ions neutralize the charge. The rate at which a charged electroscope leaf moved was measured, using radium as a standard.

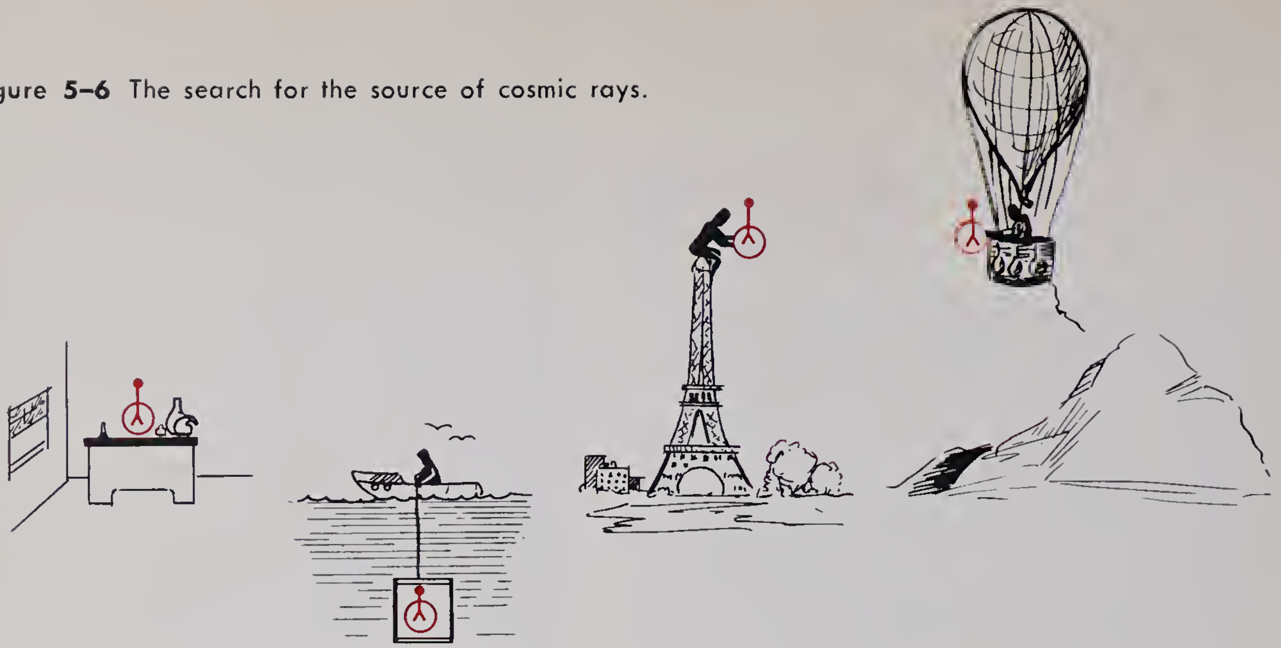
What the scientists noticed was that even when they had removed every radioactive sample from their laboratories, and when the air was dry, the electroscope leaves still went down. Perhaps radioactive ores in the ground were causing the trouble. They built special nonradioactive walls all around the electroscopes to shield them from above, below, and the sides. Still the leaves went down.

The walls they had built were thick enough to stop the rays from all radioactive substances they knew about, so these mysterious rays were more penetrating than any before studied. Were they coming from the interior of the earth or from above?

5–15 Electroscopes go down under water and up in balloons. The next step was to sink electroscopes under water. The speed of the discharge slowed down. It looked as if the rays came from above. Was it possible that the air itself was radioactive, or was the source at the surface of the earth?

Up the Eiffel Tower went a man with an electroscope. Up in balloons went others (Fig. 5–6). Millikan and some of his associates invented a self-recording electroscope and attached it to a pair of balloons that went higher than manned balloons. When one of the balloons burst, the other

Figure 5–6 The search for the source of cosmic rays.



In laboratories mysterious rays caused electroscopes to discharge slowly.

Far under water the electroscopes held their charge for a longer period of time. The mysterious rays must come from above. Did they come from the surface of the earth, from the air, or from above the air?

At the top of the Eiffel Tower, the charge was lost faster. The rays could not be coming from the surface of the earth.

As balloons rose into thinner and thinner air, the electroscopes discharged faster and faster. The rays must come from very high up.

Later balloons were sent even higher and it was found that the rate of discharge got greater and greater until it reached a maximum, and then got less. The place where it is the greatest is the region in which the primary cosmic rays are colliding with air molecules and creating the secondary cosmic rays. Above this place the air is so thin that the primary rays from outer space do not collide with many molecules, so very few ions are formed.

would let the electroscope gently down. The higher the electroscopes went, the more rapidly the leaves collapsed. Whatever this mysterious something was, it became stronger higher up. Accordingly, it could not be coming from the surface of the earth. It was also unlikely that the air was radioactive, because the effect was stronger where the air was thinner. The scientists concluded that the rays were coming from space. Millikan called them **cosmic rays**. Since gamma rays from radioactive substances are more penetrating than alpha and beta rays, Millikan and most physicists believed that these rays were probably gamma rays or something very like them.

5–16 Electroscopes go north and south. Millikan believed the cosmic rays were like gamma rays for another reason. He knew that the earth has a magnetic pole in the Arctic region. You will remember that the path of a charged particle is curved when a magnet is near (see p. 111). Therefore the earth-magnet should influence the path of charged particles, but not the path of the gamma rays. Millikan concluded that if the cosmic rays were made of charged particles, more of them would reach the earth near the poles and fewer near the equator. He tested the cosmic ray activity in various places between latitudes 41°N and 69°N, and found very little variation. This is why he felt quite sure the cosmic rays were similar to gamma rays.

Then in 1930 Compton started an investigation that covered many more locations over the earth. He found that there was a decrease in intensity near the equator and that this decrease began at about 40° latitude, where Millikan's study had stopped. Therefore Compton said that the cosmic rays must be charged particles.

This was the situation in 1931 when the American Association for the Advancement of Science met to discuss cosmic rays. Was there an angry argument between Millikan and Compton? Not at all. Instead, as a result of Compton's reports, Millikan and his workers became very busy collecting more information and soon were able to show not only that Compton was right, but that the *latitude effect*, as it was called, was even more noticeable when the observations were made from balloons.

The story of Millikan and Compton illustrates the cooperation that often exists between scientists. It is important for a scientist to be willing to change his mind when new evidence comes in, and not to be jealous of the man who finds the new evidence.

5–17 Primary cosmic rays come from outer space. Photographic plates have been sent up many miles, and then recovered and developed. In them the cosmic rays left their own records. Figure 5–7 is such a photographic record. A heavy nucleus from outer space struck a stack of photographic emulsions and plowed through them, coming to rest at the right. The man who sent the film up, developed it, and pieced it together wrote:

> The last grain at the rest point of a heavy primary cosmic particle is a thing to marvel at. Embedded within the grain of silver in the emulsion is an atom with a history unlike that of its neighbors. It is an atom which may have been blown out of a star in our galaxy millions of years ago. . . . For millions of years it escaped collision with cosmic dust. Finally it plowed into the earth's atmosphere, and in a single moment lost its store of energy accumulated since birth.[*]

Most of the particles reaching the earth are protons, a few are helium nuclei, and fewer still are nuclei heavier than helium. The charged particles from outer space are called **primary cosmic rays**. They have very great energies.

No one knows for sure where the cosmic particles originate. They come from all directions in the universe. When there is a great flare-up on our sun, there is an increase in cosmic rays, showing that many particles come from the sun. Perhaps every star in the universe is sending out these particles.

5–18 Primary cosmic rays produce secondary cosmic rays. As cosmic-ray particles come in from outer space, they travel at tremendous speeds, greater than the speed of a particle from the best man-made accelerator. High in the atmosphere they

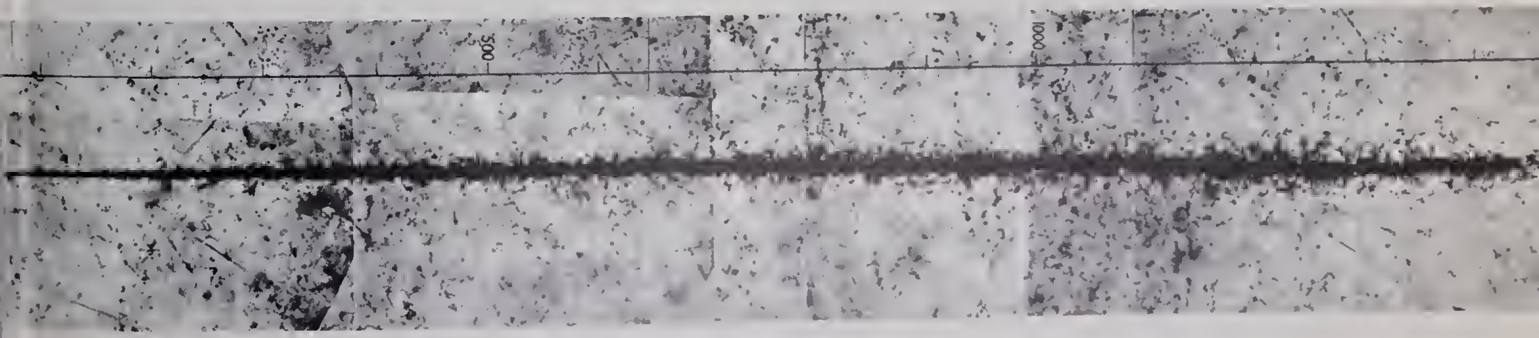


Figure 5–7 An iron nucleus in primary cosmic radiation entered the photographic emulsion from the left and finally came to rest at the right.

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[*] Herman Yagoda, *Scientific American*, May, 1956.

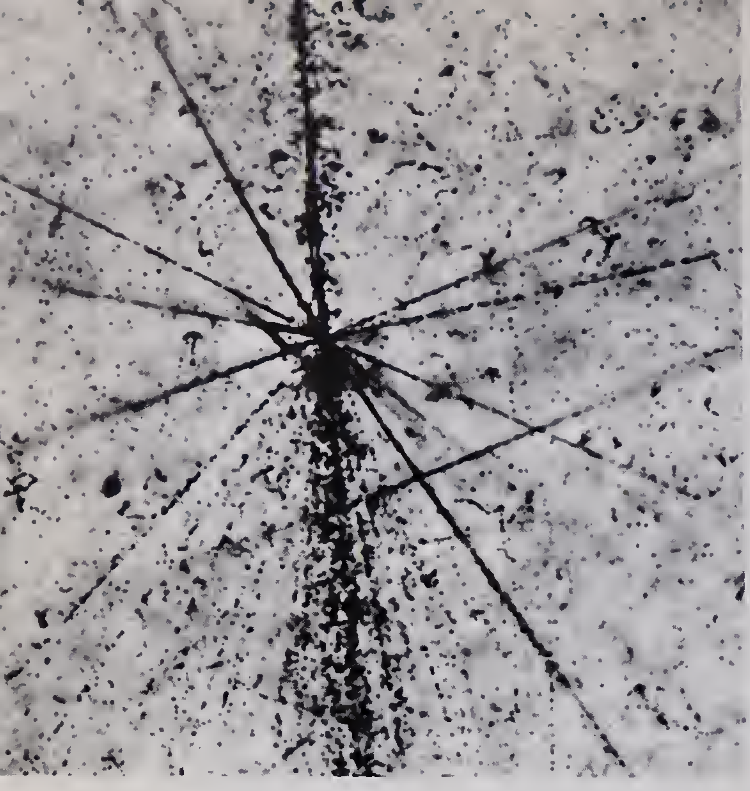

Figure 5–8 An iron nucleus of primary cosmic radiation smashed into a nucleus of the photographic emulsion and produced this "star" of nuclear fragments.

collide with air molecules. When a particle hits a nucleus, it smashes it to bits (Fig. 5–8). In such a photograph as this, the tracks of various mesons and strange particles have been discovered. Not only does the nucleus break up into pieces, but some of its mass is converted into the energy of gamma radiation.

By the time the primary rays have traveled a few miles into our upper atmosphere, nearly all of them have disappeared due to the many collisions they undergo; in their place is a multitude of particles and gamma rays resulting from these collisions. The new particles and gamma rays are called **secondary cosmic rays**. They are the ones that reach the electroscopes, cloud chambers, and counters in the laboratories, and cause the effects that started the search for cosmic rays.

A Geiger-Müller counter will always record a few particles, even when it is not in the presence of a radioactive sample. This is due to secondary cosmic rays, and is called the **background count**

Self Check

1. What original observation led finally to the discovery of cosmic rays?
2. How did scientists discover that cosmic rays come from outside the earth?
3. Why did they conclude that primary cosmic rays were charged particles?
4. What kind of charged particle is most common in primary cosmic rays? What kind is the next most common?
5. What is an unsolved problem about cosmic rays?
6. What are secondary cosmic rays?
7. What is meant by background count?

Nuclear Energy from Fission

5–19 Hahn and Strassmann discover nuclear fission. The chemists Hahn and Strassmann hardly dared to believe what they had found. Could this be barium? They had bombarded uranium with neutrons from artificially radioactive isotopes. The uranium nuclei absorbed neutrons and then exploded, forming other elements. One of the new substances seemed to be radium, but when they analyzed it carefully, they found it to be barium. "As chemists," they wrote in 1939, "we must say that the product is barium, not radium, but as nuclear chemists — we cannot bring ourselves to make this leap in contradiction to all previous lessons of nuclear physics. Perhaps, after all, our results have been rendered deceptive by a series of strange accidents."*

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* Gordon Ferrie Hull, *Elementary Modern Physics*, The Macmillan Co., 1949, p. 398.

Why should these men be surprised to find barium coming from uranium? The atomic number of barium is 56. Uranium is number 92. All nuclear changes up until then had involved adding or subtracting one or two atomic numbers. Here was a change of 36.

Lise Meitner had worked with these men in Germany. But she was partly Jewish and so was not wanted in Hitler's Reich. Carrying with her the knowledge of the work in Berlin, she went to Denmark and discussed it with Otto Frisch, another refugee from Hitler. Together they puzzled out what was happening to uranium.

They started out by agreeing that barium was coming out of the uranium. The difference of 36 in the atomic numbers corresponds to that of krypton. Now if you look at the graph of binding energies on p. 103 (Fig. 4–22), you will see that barium and krypton are higher on the curve than uranium. An element high on the curve has a smaller mass per nucleon than one low on the curve. Therefore Meitner and Frisch concluded that a large amount of energy should be released when an atom of uranium is split into two middle-sized atoms. They repeated the experiment, this time measuring the energies of the particles, and found that they were large. (They did this on a small scale, so there was no loud explosion, just some particles that ionized more air than less energetic ones could possibly do.)

Try some more arithmetic, using the common isotopes of uranium, barium, and krypton:

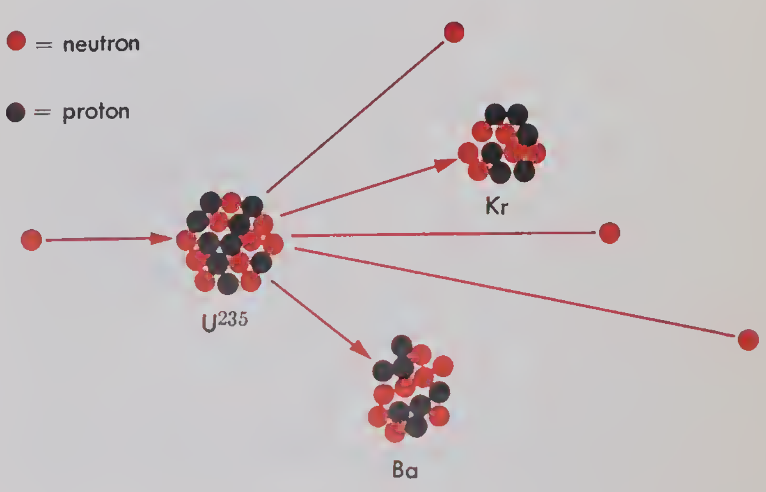
	$_{92}U^{238}$	$_{56}Ba^{138}$	$_{36}Kr^{84}$
Mass number	238	138	84
Protons in nucleus	92	56	36
Neutrons in nucleus	146	82	48

Barium 138 and krypton 84 together have 82 + 48 or 130 neutrons. U^{238} has 146, 16 more. Frisch and Meitner did not know what isotope of uranium had split or what isotopes of krypton and barium were formed, but from calculations like this they felt quite sure that when an atom of uranium was split by a neutron, the products should be two middleweight atoms, energy, and more neutrons. Here, for the first time in the great nuclide hunt, a bullet (the original neutron) caused a reaction that produced more bullets.

Meitner and Frisch named the splitting of the uranium nucleus **fission** and cabled the exciting news to Niels Bohr (Frisch's father-in-law and at the time the world's greatest atomic physicist) who was visiting Einstein at Princeton. Bohr announced it at a meeting of physicists in Washington, D.C., in January, 1939. When other scientists checked the results, they found that the uranium nucleus really had been split, and that enormous energy and more neutrons were produced. The 16 extra neutrons that show up in the arithmetic above are really more than actually occur. The isotopes formed have more neutrons than the most common kinds. On the average, two to three neutrons are released when one uranium nucleus splits (Fig. 5–9).

The products of uranium fission are not always barium and krypton. Sometimes they are strontium, atomic number 38, and

Figure 5–9 A neutron strikes an atom of uranium 235 and causes it to split.



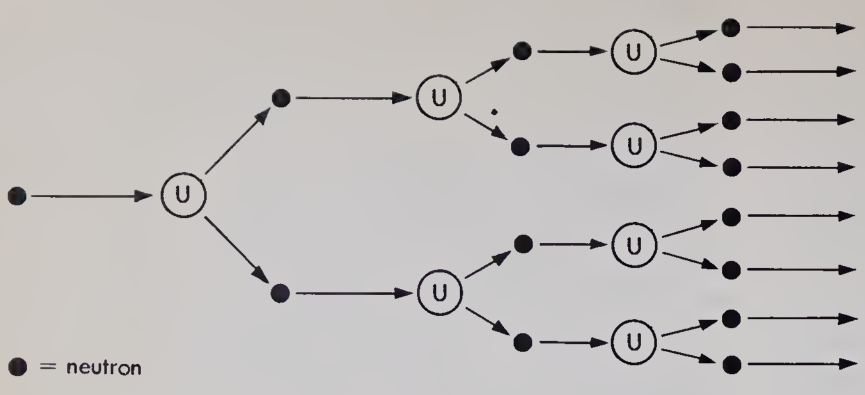


Figure 5–10 The chain reaction: A neutron hits a uranium atom. Suppose two neutrons are emitted when the atom splits. Each of these causes the splitting of another uranium atom. This continues until many atoms have split. In a nuclear bomb the whole process, involving the splitting of millions of atoms, occurs in a tiny fraction of a second.

xenon, atomic number 54. There are other pairs as well. In each case the two atomic numbers add up to 92; also in each case neutrons are released.

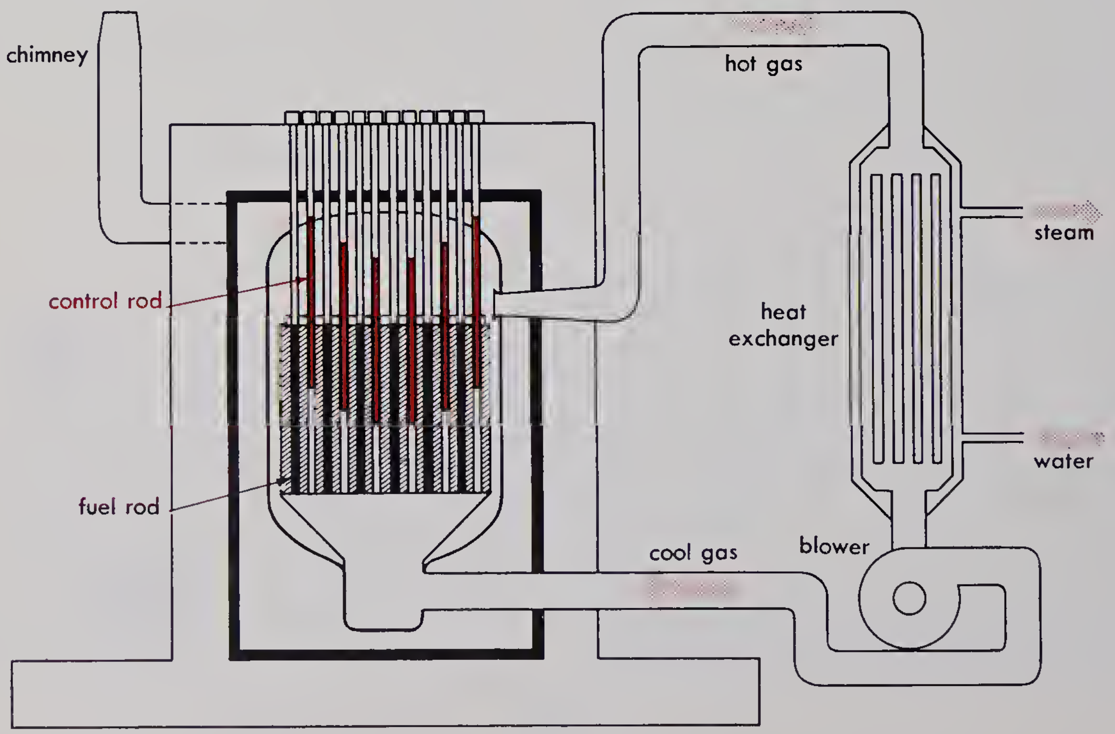
5–20 Chain reactions can be controlled. The discovery of nuclear fission was very exciting to scientists because:

1. More energy is released by fission than by ordinary radioactivity.
2. The fission of an atom is caused by one neutron. When the atom explodes, it produces one to three neutrons. If these can be used to explode more atoms, the reaction, once started, will continue until all the atoms are used up. This is called a **chain reaction** (Fig. 5–10).

If a chain reaction builds up rapidly, there is a sudden great release of energy. This is what happens in a fission bomb.

For a nuclear reaction to be useful for anything but destruction, however, it is necessary to control the chain reaction. The apparatus in which a controlled fission takes place is called a **nuclear reactor**, or **nuclear pile**. The reactor contains the uranium or other nuclear fuel, sealed in metal

Figure 5–11 A nuclear reactor is regulated by control rods which capture neutrons. The reaction can be slowed down by pushing in the rods and speeded up by pulling them out. Rods are made of cadmium, boron carbide, or hafnium. The whole pile is shielded by thick walls of concrete.



(Redrawn from p. 58, *Scientific American*, October, 1955, with permission of the publishers and by Oak Ridge National Laboratory, operated by Union Carbide Corporation for the Atomic Energy Commission.)

containers. Between these containers are **control rods** made of a substance that absorbs neutrons (Fig. 5–11). The rods can be pushed in or pulled out. When they are all the way in, they capture neutrons about as fast as they are produced. As a result, when atoms of uranium split and produce neutrons, almost none of the neutrons are able to reach another uranium atom. The reaction soon dies out.

Now if the rods are pulled out, more and more of the neutrons reach other uranium atoms, and a chain reaction starts and grows, producing heat which can be used to run steam turbines on ships, electric power plants, or other large machinery. If the rods are left pulled out, the chain reaction keeps on growing, with the reactor getting hotter and hotter and hotter. To prevent this, when the reactor has warmed up to the desired temperature, the rods are pushed in slightly. The purpose is to adjust the reaction so that, on the average, exactly one neutron per fission will reach another uranium atom and cause it to split. From then on, the reactor produces heat at a steady rate and will neither overheat nor cool down.

It was soon discovered that the uranium which was being split by neutrons was U^{235}. This was unfortunate from the point of view of cost because in natural uranium there is almost 140 times as much U^{238} as U^{235}. Separation of these isotopes was one of the big problems of the early development of nuclear energy. They cannot be separated by chemical methods because they are chemically alike. All the methods used to separate the two isotopes depend on the small difference in their mass. One way is to prepare compounds of uranium that are gases and pass them through porous barriers. The molecules containing U^{235}, being slightly lighter, move more rapidly and get through faster. Therefore the gas that comes through first is slightly richer in U^{235} than before. This is repeated thousands of times, until the gas coming through the last barrier has almost no U^{238}.

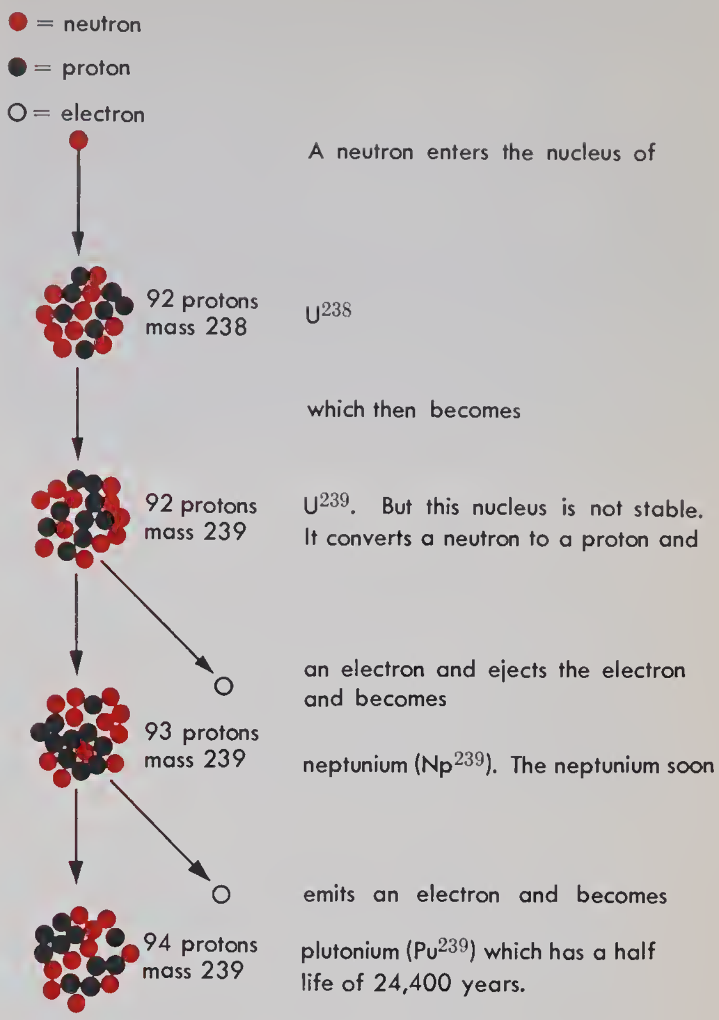

● = neutron
● = proton
○ = electron
A neutron enters the nucleus of
92 protons
mass 238
U^{238}
which then becomes
92 protons
mass 239
U^{239}. But this nucleus is not stable. It converts a neutron to a proton and
an electron and ejects the electron and becomes
93 protons
mass 239
neptunium (Np^{239}). The neptunium soon
emits an electron and becomes
94 protons
mass 239
plutonium (Pu^{239}) which has a half life of 24,400 years.

Figure 5–12 This diagram shows formation of neptunium and plutonium.

5–21 Reactors produce plutonium. In 1940 two new elements with atomic numbers 93 and 94 were found. How they are made is shown in Fig. 5–12. The new elements were named neptunium (Np) and plutonium (Pu). (The three outermost planets are Uranus, Neptune, and Pluto; thus the three elements: uranium, neptunium, plutonium.) Neptunium has a short half-life and therefore does not exist long enough to be useful as a source of atomic energy. Plutonium, with a half-life of 2.44×10^4 years, turned out to be very useful. Like U^{235}, Pu^{239} can be split by slow

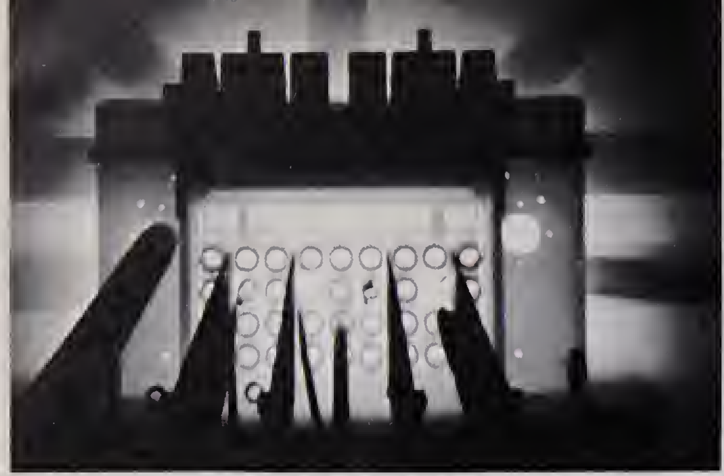


Figure 5–13 A nuclear pile surrounded by a moderator of heavy water. Note the glow of the operating pile.

neutrons into two middle-sized atoms, giving off large quantities of energy. And since it is chemically different from uranium, the two elements can be separated fairly easily. Elements with higher atomic numbers than plutonium have also been discovered as a result of nuclear bombardment. See Table 4–1, p. 95.

5–22 Slow neutrons cause fission. A neutron emitted from a splitting uranium or plutonium nucleus travels faster than 4,000,000 meters per second. A neutron moving this fast rarely causes fission of another atom. Therefore, in a reactor, a **moderator** is used to slow the neutrons down to about 2000 meters per second. Graphite (a form of carbon) and heavy water (water made of deuterium and oxygen) are often used as moderators (Fig. 5–13). Fast neutrons collide with atoms of the moderator, causing the neutrons to slow down.

Notice one important difference between the control rods and a moderator. The atoms of the control rods absorb neutrons; those of the moderator do not absorb them, but merely slow them down through collision.

Although fast neutrons are much less likely to cause fission than slow ones, they can cause a chain reaction in pure U^{235} or Pu^{239}. In a nuclear bomb pure materials are used without a moderator. The reaction must take place quickly (before the bomb can break apart, scattering unused uranium or plutonium) and fast-moving neutrons make this possible.

5–23 There is a critical size for a chain reaction. Not every lump of U^{235} in which an atom has been exploded by a neutron undergoes complete fission. If the lump is too small, most of the neutrons escape. Also, if too many impurities are present, they will absorb some of the neutrons. For the chain reaction to occur, then, two conditions are necessary:

1. The material must be pure enough so that most of the neutrons are not captured by nonfissionable atoms.
2. The size of the material must be large enough so that most of the neutrons do not escape from it.

The smallest possible amount of fissionable material that will allow the chain reaction to continue is called the **critical size.** The exact method by which a fission bomb is triggered is a military secret. What is known is that two or more lumps of fissionable material are placed in the bomb. Each lump is below critical size. The bomb is set off by having these lumps suddenly brought together to make one lump which is above critical size.

So far nothing has been said about how to obtain the first neutron to start a chain

Figure 5–14 A nuclear reactor plant used for the commercial production of power.

reaction. It is not necessary to do this. There are always a few free neutrons being formed in any material as a result of cosmic rays or radioactivity. If the material is below critical size, a reaction caused by one of these neutrons dies out, but if it is of critical size, the reaction grows.

5–24 Nuclear reactors are becoming increasingly useful. Reactors are used for three main purposes:

1. Finding out how to build better reactors
2. Producing radioactive nuclides
3. Producing energy

The first reactor was built merely to answer the question: Will it work? It was built secretly during World War II under the football stadium of the University of Chicago. Enrico Fermi was in charge. It did work, showing that nuclear energy was practical. Nearly every reactor today is an experimental one. New designs are tried in an attempt to make them better. Most of them are **breeder reactors**, that is, reactors which produce more nuclear fuel than they use. The one shown in Fig. 5–14 has a core of rather pure U^{235}. Outside of this is natural uranium, which is largely U^{238}. The reaction starts in the core. Then, as neutrons escape into the U^{238}, they cause the production of plutonium. As the U^{235} is used up, it produces an even larger quantity of fissionable plutonium as well as heat energy that can be used for making electricity. As the plutonium in its turn undergoes fission, some of its neutrons also convert more U^{238} to plutonium. When all the U^{238} has been converted to plutonium, the reactor no longer breeds fuel, unless more U^{238} is added to keep the reaction going. Other breeder reactors use the common isotope of thorium, Th^{232}, in place of U^{238}. It absorbs neutrons from the core and is converted into U^{233}, another fissionable isotope of uranium.

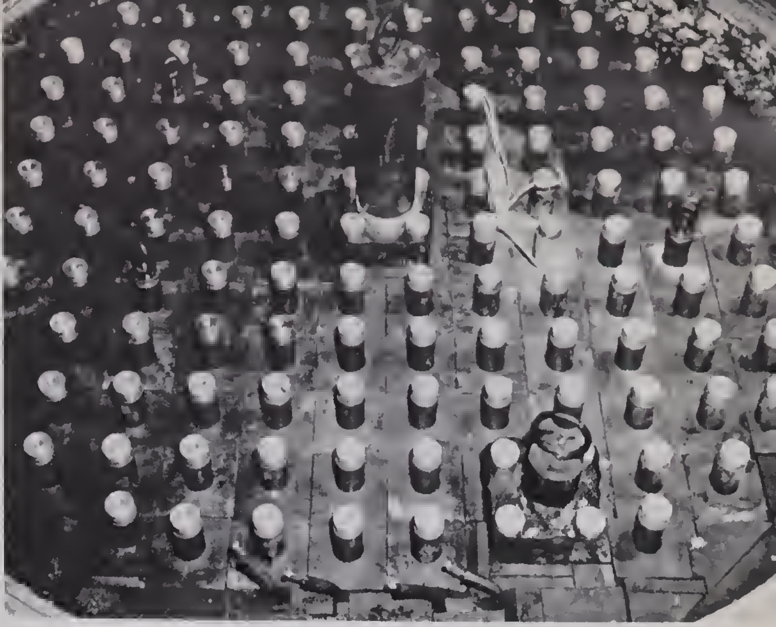


Figure 5–15 The top of a nuclear reactor showing in the center the thimble by which materials can be lowered into the reactor to be made radioactive.

Figure 5–15 shows a reactor that is used primarily to produce nuclides. The "thimble" in the center is a hole into which various materials can be lowered. Then neutrons from the reactor bombard the materials, producing many nuclides, most of them radioactive. One very powerful radioisotope is cobalt 60. This has been used to irradicate plants in order to find out the effect on their growth (Fig. 5–16).

Figure 5—16 Cobalt 60 from the pipe gives off gamma rays which produce genetic changes in the plants exposed.

A nuclear reactor produces a great deal of heat, which in turn is used for power production. In nuclear surface vessels and submarines, for example, this heat is used to run steam turbines. The heat from a reactor can also be used to run an electric power plant. Not many reactors for producing power have been built because at present it is cheaper to use coal, oil, or water power to run such plants. With more research, the cost of these plants will come down, and they will then be economical to run.

5–25 Nuclear bombs are extremely destructive. One cubic inch of uranium used in a bomb produces as much energy as 9000 tons of TNT, the explosive commonly used in the older kinds of bomb. Fission bombs are destructive in four ways: heat, blast, immediate radiation, and delayed radiation (largely fallout).

The explosion itself is tremendously hot, certainly in the millions of degrees. At the center of the blast, even sand and brick are melted. Air heated by the explosion expands very quickly. This sends a wave of air out in all directions with such force that it levels buildings at a considerable distance. The immediate radiation from the bomb is largely neutrons and gamma rays.

Heated air from the vicinity of the blast rises, carrying radioactive material with it, and forming a great mushroom cloud. The isotopes formed by the fission process are radioactive and decay into other radioisotopes. The materials of the bomb casing may become radioactive. Many of these radioactive elements linger in the ground near the explosion for years. Others are sucked up into the mushroom cloud and travel in the upper atmosphere around the earth, slowly dropping to the ground. This is called **fallout**.

Most of the fallout occurs near the bomb, but much of it may come down thousands of miles away over a long period of time. The later fallout does not do much damage if the isotope has a short half-life. Strontium 90, however, has a half-life of 28 years. Chemically it is very much like calcium, and if a person eats food containing strontium 90, it may take the place of calcium in his bones and become a permanent part of his body, exposing the bones to beta rays for a long period of time. This is why people are concerned more about strontium 90 than about many of the other fallout isotopes. Iodine 131, which can cause thyroid gland cancer, and strontium 89 are also found in fallout, but have less lasting effect because they have short half-lives (8 days for I^{131} and 50 days for Sr^{89}). While the amount of radioisotopes so far created by bomb explosions is small, the amount could become very dangerous if too many bombs are exploded.

5–26 Radiation damage can be prevented. Radioactive isotopes, x-ray machines, and nuclear reactors must be shielded so that dangerous radiation does not reach the people who operate them. Alpha and beta rays can be stopped by thin shields (see Sec. 5–3), but x-rays, gamma rays, and neutrons are more penetrating. Neutrons from a reactor are controlled by reflecting them back into the reactor, often by a layer of graphite. The ability of a shield to stop x-rays and gamma rays depends on its thickness and its density. The more mass there is between a person and a reactor, the better he is protected.

Gamma rays are very penetrating. Their intensity can be cut down to $1/_{100,000}$ of their original value if the source is surrounded by 10 inches of lead. If concrete is used, however, it must be 47 inches thick to provide the same protection. This is because concrete is only about one fifth as dense as lead. Notice that by using lead a reactor designer cuts down the space occupied by the shield, but he does not significantly cut down its weight. If he were to use a shield of a material much lighter than lead or concrete, aluminum, for example, he would have to make the wall thicker still. This is why fission power has not been used on lightweight vehicles such as automobiles. The necessary shielding is too heavy, no matter what material is used.

5–27 The nuclear bomb has peacetime uses. When chemical explosives like gunpowder were first invented, they were used for war. Today chemical explosives such as TNT and dynamite are more widely used for mining and excavation than for war. Some people think that the same thing may happen with nuclear bombs. Nuclear bombs exploded deep beneath the surface of the earth do not send isotopes to the surface. They melt the rock around them and when the rock hardens, it seals in the isotopes. The rock above the explosion breaks up into small pieces. This might make it easier to get out minerals or to use some oil shales that are now too expensive to utilize.

Self Check

1. Why were Hahn and Strassmann reluctant to believe that they had produced an isotope of barium by bombarding uranium with neutrons?
2. What are the two important facts about nuclear fission that made this discovery exciting?
3. What is the smallest possible number of neutrons that must be released at each fission in order to keep a chain reaction going?
4. Why is this number too small to be useful practically?
5. What is a nuclear reactor?
6. What is the function of control rods in a reactor?
7. Why is a moderator needed in a reactor?
8. What is the fissionable isotope of natural uranium?
9. How is plutonium produced?
10. Why will a mass of uranium that is smaller than critical size not permit a chain reaction to exist?
11. What are the three principal uses for nuclear reactors?
12. How does a breeder reactor work?
13. What is fallout?
14. Why is Sr^{90} a very undesirable part of fallout?
15. Why has fission power not been used to propel automobiles?
16. What is a possible constructive use of nuclear bombs?

Problems

Ⓐ 1. Write the equations of the reactions shown in Fig. 5–12.

2. Is a slow neutron really slow? Find the speed in miles per hour of a "slow" neutron traveling at 2000 meters per second.

Discussion Questions

1. How many neutrons must the fissionable material of a breeder reactor produce per fission? Explain your answer.
2. How might geography influence the question of whether or not it is economical to build a nuclear reactor?
3. A few years ago a man who worked at a nuclear reactor had some radioactive material spilled on his clothes without his knowing it. He became sick, but later recovered. His clothes were destroyed and his home carefully inspected and declared free from contamination. In spite of this, his neighbors were afraid to visit him and when he moved no one would buy his house. Were people justified in their fear?

Fusion Energy

5–28 Fusion requires high temperature. **Fusion** is the combining of light elements to make heavier ones. This means that the nuclei must join together. But nuclei have positive charges, and Coulomb's law says that the closer these charges get, the more they repel each other. In fact, according to this law, only an infinite force can bring two positive charges together. Yet we know that heavy nuclei contain many protons. There must be another force, which acts in opposition to the **Coulomb force**, that holds nuclei together. This force apparently is weaker than the Coulomb force when the particles are at a distance, but becomes stronger at close range. Just how this force operates is one of the incompletely solved mysteries of physics.

For fusion to take place, the positive charges must be brought close enough together so that the **nuclear force** can act. High speed turns the trick. Get two atoms moving fast enough, and they may come close together and fuse. Atoms move faster when they are hot, so the secret is to get the temperature up into the millions of degrees. For this reason, fusion is called a **thermonuclear reaction.** The stars, including our sun, are at the necessary temperature. There fusion occurs continuously, keeping the stars hot. A number of fusion reactions take place with the final result being the production of helium from hydrogen. In the process, some of the mass is converted to energy.

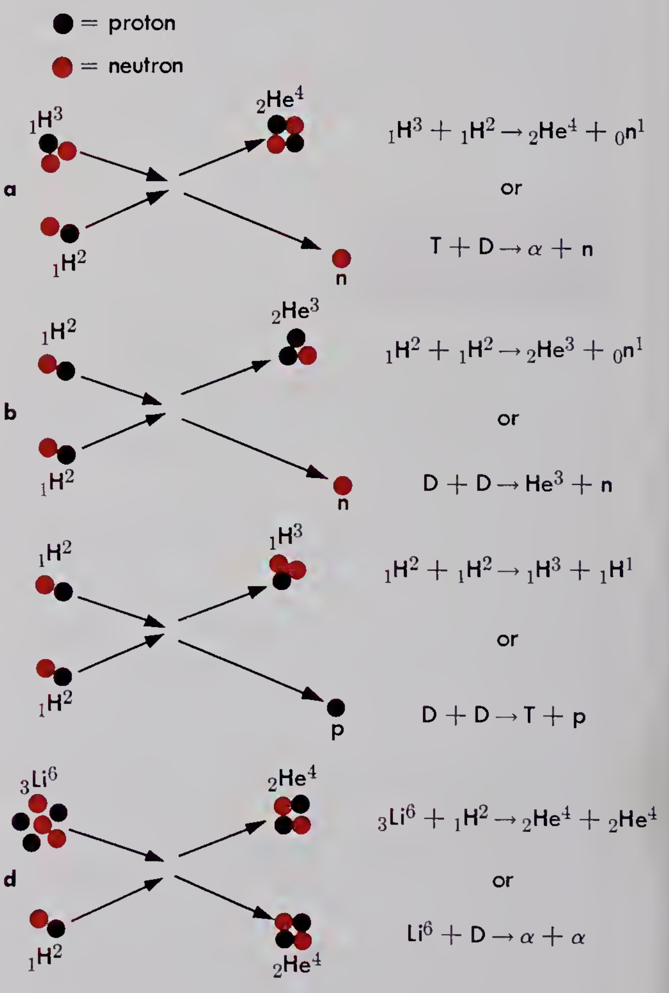
5–29 Deuterium and tritium are fusion materials. Since ordinary hydrogen nuclei fuse too slowly, even at high temperatures, the heavier isotopes of hydrogen are usually used. Some of the reactions are illustrated in Fig. 5–17. Take the first of these and see how it produces energy:

$$\begin{array}{ccccccc} {}_1\mathrm{H}^3 & + & {}_1\mathrm{H}^2 & \rightarrow & {}_2\mathrm{He}^4 & + & {}_0\mathrm{n}^1 \\ &&&&&& + \text{ energy} \\ \text{tritium} & & \text{deuterium} & & \text{helium} & & \text{neutron} \\ 3.01605\ \mathrm{u} & + & 2.01410\ \mathrm{u} & \rightarrow & 4.00260\ \mathrm{u} & + & 1.00867\ \mathrm{u} \\ &&&&&& + \text{ energy} \end{array}$$

$$5.03015\ \mathrm{u} \rightarrow 5.01127\ \mathrm{u} + \text{energy}$$

After the tritium and deuterium atoms have fused to make an atom of helium, with a

Figure 5–17 These fusion reactions may be used in the production of power or in H-bombs.


● = proton
● = neutron
a
$_1H^3$
$_1H^2$
$_2He^4$
n
$_1H^3 + {}_1H^2 \rightarrow {}_2He^4 + {}_0n^1$
or
T + D → α + n
b
$_1H^2$
$_1H^2$
$_2He^3$
n
$_1H^2 + {}_1H^2 \rightarrow {}_2He^3 + {}_0n^1$
or
D + D → He^3 + n
$_1H^2$
$_1H^2$
$_1H^3$
p
$_1H^2 + {}_1H^2 \rightarrow {}_1H^3 + {}_1H^1$
or
D + D → T + p
d
$_3Li^6$
$_1H^2$
$_2He^4$
$_2He^4$
$_3Li^6 + {}_1H^2 \rightarrow {}_2He^4 + {}_2He^4$
or
Li^6 + D → α + α

neutron left over, the mass is less than at the start. This mass difference (5.03015 u − 5.01127 u = 0.01888 u) is converted to energy. The difference seems very slight, and it is, but the amount of energy produced is very large. The conversion of 1 g of tritium and deuterium fuel into helium and neutrons would supply electric energy to an average home for 38 years.

5–30 At fusion temperatures, matter becomes a plasma. How can the temperature be made hot enough for a fusion reaction? A uranium or plutonium bomb can do it. The hydrogen bomb, or H-bomb, consists of a fission bomb to provide the high temperature, plus the fusion materials. The exact contents are a military secret, but it may include lithium as well as deuterium or tritium.

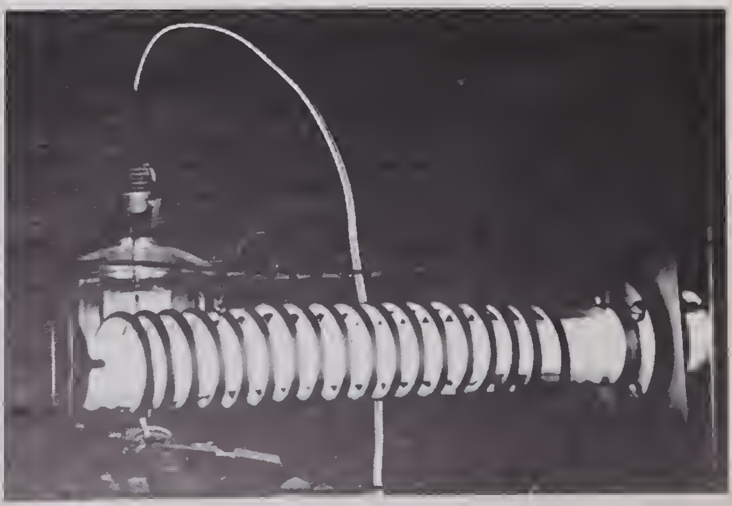
As an alternative to using fission bombs to produce the necessary high temperature, scientists are using electrical and magnetic methods to get deuterium and tritium hotter and hotter. They have to be careful that none of this hot material touches the walls of the apparatus, for then the walls would melt. The deuterium and tritium atoms vibrate so fast that they lose their electrons, becoming ions. This almost completely ionized gas consisting largely of nuclei and electrons is called a **plasma**.

As the plasma rushes along through a tube, magnetic fields keep it pushed toward the center of the tube, so that it cannot touch the walls. Figure 5–18 shows the glow of a hot plasma traveling down the center of a tube. Up to now several machines have produced temperatures above a million degrees, but the necessary goal may be as much as a hundred million degrees. When that goal is reached, a breakthrough will have been made in using fusion for other purposes besides bombs.

5–31 Nuclear fusion may become a power source. There are several advantages of nuclear fusion as a source of power. One is that the fuel supply is practically unlimited and cheap to obtain. Fewer than one molecule in ten thousand of natural hydrogen is deuterium, but not much is needed. The deuterium in a gallon of water costs about four cents to extract and would give as much energy as more than three hundred gallons of gasoline! It has been calculated that there is enough deuterium in the ocean to supply the energy needs of the world for twenty billion years at our present rate of energy consumption.

The by-products of producing energy by nuclear *fission* are difficult to handle and dispose of. When uranium or plutonium atoms are split, the fragments are radioactive. They must be removed from a reactor as the fuel is used up. Some are buried deep in the earth and others are sunk in the ocean. In time they may cause a dangerous amount of radioactive pollution. If a *fusion* reactor can be built, on the other hand, this problem would not exist. The products are ordinary helium atoms plus a few neutrons. Helium gas can be allowed to escape, or can be captured for use. It is completely harmless. The neutrons will react with the walls of the apparatus to form a few radioactive isotopes, but the quantity will be small compared with the fragments from fission reactions. See the chart on fusion and fission on page 132.

Figure 5–18 A plasma contained in a quartz tube produced the glow shown below.



COMPARISON OF FUSION AND FISSION

	Fusion	*Fission*
What happens	Light nuclei form heavier ones	Very heavy nuclei are split into middle-weight ones
Comparison of energy produced per gram of fuel	Greater	Less
Materials used	Deuterium, tritium, lithium	U^{235}, Pu^{239}, and some others
Availability of materials	Almost unlimited. Cheap to obtain.	Good sources are limited. Expensive. Very large quantity of low-grade ores exists.
How the reaction starts	Occurs naturally if the temperature is high enough and particles not too far apart. High temperature in bomb obtained by use of fission bomb to start reaction. In reactor, the temperature is obtained by electric and magnetic heating action.	Occurs when a neutron is absorbed by a nucleus.
How the reaction is kept going	By confining the hot plasma so that it cannot cool.	Chain reaction when material is of critical size and neutrons are slowed by moderator.
How controlled	By magnetic fields.	By control rods that absorb neutrons.
Radioactive isotopes formed	Almost none	Many
Shielding required?	Yes, because neutrons from the process can make the walls radioactive.	Yes, because fission products are radioactive.
Possibility of useful energy production	Now in research stage. When made practical, direct generation of electricity without having to heat steam is theoretically possible.	Reactors now in use to operate steam turbines in ships and power plants. At present it is more expensive to produce electricity this way than by older methods.

Self Check

1. Why does fusion require a very high temperature before it can start?
2. Where in the universe is fusion the chief source of energy?
3. What are some of the nuclides used as fusion fuels?
4. What produces the necessary high temperature in an H-bomb?
5. What is plasma?
6. Which is a greater radioactive hazard, fusion or fission?
7. How is a fusion reaction controlled?

Problems

In solving these problems, refer to Table 4–4, p. 101 and the data at the top of p. 130.

A **1.** The sun's energy is probably produced as a result of the "proton-proton" chain of reactions. Write the equations: (a) A proton combines with a proton; (b) the resulting nucleus emits a positron; (c) the resulting nucleus combines with another proton; (d) two of the resulting nuclei combine and emit two protons.

2. Lithium 7 has a mass of 7.01601 u. It can combine with hydrogen 1 to produce two helium atoms. Find the mass loss in u.

3. Helium 3 has a mass of 3.01603 u. How much mass is converted to energy in reaction **b** of Fig. 5–17? In reaction **c**?

B **4.** Cockcroft and Walton produced the reaction of Problem 2, and measured the energy of the alpha particles by observing their cloud tracks. Each particle had an energy of 1.38×10^{-5} ergs. Show that this agrees with the $\Delta E = \Delta mc^2$ relationship fairly well.

Discussion Questions

1. If the soil has been contaminated by Sr^{90}, authorities recommend deep plowing in order to make the soil safe to use. Why does this help?
2. If a fusion reaction produces no radioactive isotopes, how can a hydrogen bomb produce radioactive fallout?

Chapter Summary

The nucleus of a radioactive substance spontaneously decays, giving off various kinds of radiation and becoming transformed into the nucleus of another element. Among the kinds of radiation are alpha particles (helium nuclei), beta particles (electrons), and gamma rays (something like light). Uranium and radium (discovered by the Curies) are two important naturally radioactive substances. The rate of decay is measured in half-lives. Rays from radioisotopes are dangerous to living things, but are also useful in a variety of ways.

Bombardment of nuclei by various particles has resulted in the production of artificially radioactive isotopes. It also resulted in the discovery of the neutron. Artificial radioisotopes have many uses. Some artificially radioactive isotopes give off positrons when they decay.

Primary cosmic rays are positively charged particles which enter our atmosphere at great speed and produce secondary cosmic rays when they react with the atoms of the upper atmosphere. Secondary cosmic rays are responsible for the background count of a G-M tube or other counter.

Fission of U^{235} and Pu^{239} by slow neutrons produces a large quantity of energy due to mass loss. Neutrons released by the process cause a chain reaction. The process is used in fission bombs and in nuclear reactors. In reactors the neutrons are slowed by a moderator and absorbed by control rods that regulate the rate of fission activity. A mass of fissionable material must be at least of critical size before a chain reaction can continue. A breeder reactor produces more fissionable material than it consumes as fuel. Reactors are used for a variety of purposes.

Fission products are radioactive and cause a dangerous fallout in the case of bombs. Shielding is the best protection against radiation.

Fusion of light elements also produces energy from mass loss and is the source of energy of stars. Coulomb forces tend to keep the particles from coming together, but the high velocities they have when hot make it possible for particles to get close enough for nuclear forces to hold them together. In an H-bomb the temperature is raised by using a fission bomb. A fusion reactor will create a high temperature in a plasma controlled by magnetic fields. Fusion produces almost no radioactive isotopes.

Vocabulary

fluorescent (*p. 109*)
uranium (*p. 109*)
radium (*p. 110*)
radioactivity (*p. 110*)
alpha rays (*p. 111*)
beta rays (*p. 111*)
gamma rays (*p. 111*)
radioactive element (*p. 111*)
radioisotope (*p. 112*)
stable isotope (*p. 112*)
radioactive decay (*p. 112*)
half-life (*p. 112*)
G-M counter (*p. 113*)
artificial radioactivity (*p. 116*)
primary cosmic rays (*p. 121*)
secondary cosmic rays (*p. 122*)
background count (*p. 122*)
fission (*p. 123*)
chain reaction (*p. 124*)
fission bomb (*p. 124*)
nuclear reactor (pile) (*p. 124*)
control rods (*p. 124*)
moderator (*p. 126*)
slow neutrons (*p. 126*)
fast neutrons (*p. 126*)
critical size (*p. 126*)
breeder reactors (*p. 127*)
nuclear bomb (*p. 128*)
fallout (*p. 128*)
strontium 90 (*p. 128*)
fusion (*p. 130*)
Coulomb force (*p. 130*)
nuclear force (*p. 130*)
thermonuclear reaction (*p. 130*)
H-bomb (*p. 131*)
plasma (*p. 131*)
fusion reactor (*p. 131*)

Problems

A Write equations for the following:

1. Strontium 90 is radioactive and gives off an electron when it decays.

2. U^{232} gives off an alpha particle when it decays.

3. Thorium 232 decays to lead 208 as a result of the following emissions: (a) alpha; (b) beta; (c) beta; (d) alpha; (e) alpha; (f) alpha; (g) alpha; (h) beta; (i) beta; (j) alpha.

4. Li^7 bombarded by a proton gives off an alpha particle.

5. Cu^{65} bombarded by a neutron gives off a proton.

6. Lithium 6 has a mass of 6.01512 u. How much mass is converted to energy in reaction **d** of Fig. 5–17?

B **7.** A G-M counter records 20 counts per minute when no radioactive sample is near it, 100 counts per minute when sample A is near it, and 300 counts per minute when sample B is near it. Compare the radioactivity of sample B with that of sample A.

8. Write the equations of Fig. 5–17 in shorthand form.

9. Find the percent of original mass that is converted to energy in each of the reactions of Fig. 5–17. Which is the best energy-producer?

Discussion Questions

1. Dating of ancient objects by the use of C^{14} is accurate only up to about 30,000 years. Why?
2. In Fig. 5–5 do the mesons formed by the neutron collision have positive or negative charges? How can you tell?
3. How can the neutron collision with a hydrogen nucleus in Fig. 5–5 produce 1 proton and 2 mesons? The neutron itself bounced off.
4. How might world tensions influence the question of whether or not to build a nuclear reactor?
5. Do you feel that the discovery of nuclear energy was good or bad for man?
6. How would you go about measuring the radioactivity of a sample of rock with an electroscope?

PHYSICS HALL OF FAME

Enrico Fermi · 1901–1954

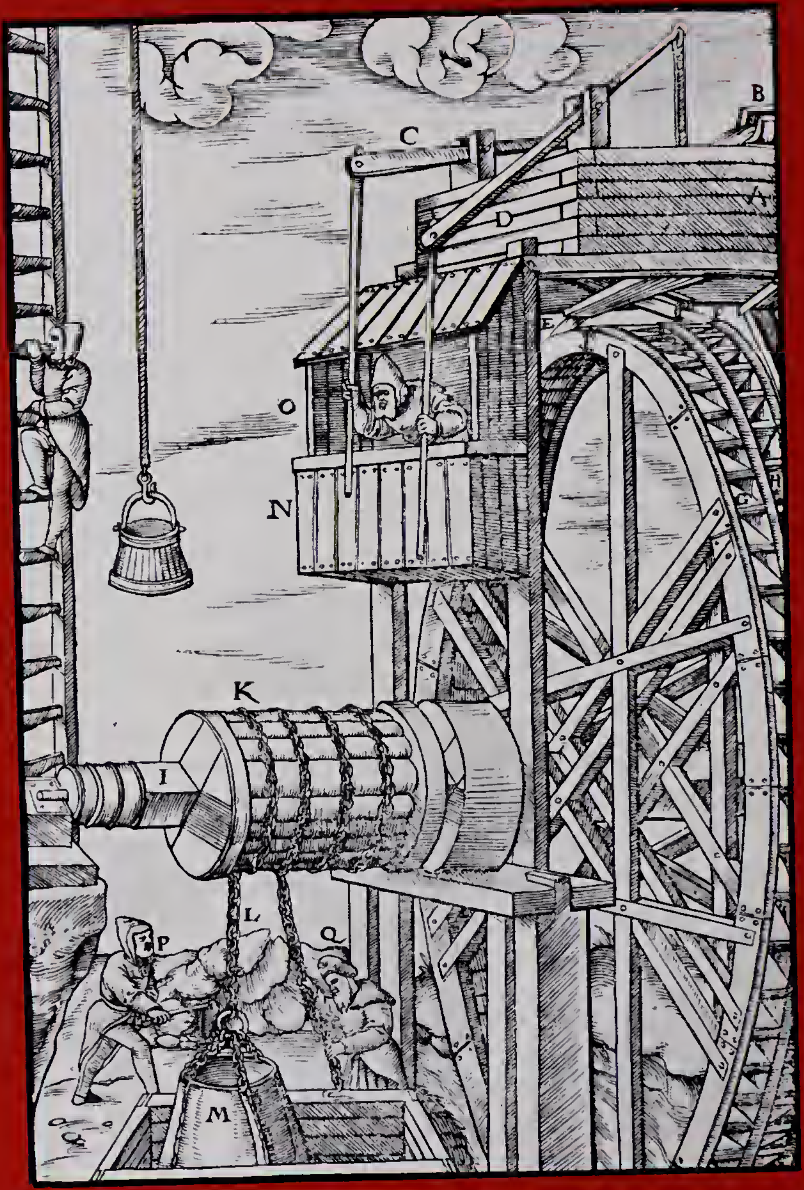
One of the most eager of the "isotope hunters" was the Italian-born physicist Enrico Fermi. His favorite "bullet" was a beam of neutrons; by this means, he and his co-workers changed the nuclei of about fifty different elements. The 1938 Nobel Prize in Physics was awarded to Fermi for this work.

In his experiments of the 1930's Fermi had observed that when a nucleus absorbed a neutron and exploded, its atomic number changed by only one or two units. Therefore, he was very much interested by the announcement, in 1939, of the phenomenon of nuclear fission. Together with Hungarian-born physicist Leo Szilard, Fermi successfully repeated the fission experiments of Hahn and Strassmann, Meitner and Frisch. Fermi and Szilard found, as the others had predicted, that neutrons are released when the uranium atom is split; and they at once foresaw the possibility of a chain reaction.

Fermi and Szilard understood the tremendous quantities of energy that an atomic chain reaction might liberate. Europe was at war. Both men had immigrated to the United States to escape political oppression, and to them the prospect that Hitler or Mussolini might have access to such a weapon as an atomic bomb was horrifying. Thus, Fermi and Szilard felt that the United States must work quickly and secretly to make use of their discovery. How could they get action? Szilard went to Albert Einstein with a manuscript describing what he and Fermi had discovered. Einstein immediately wrote to President Roosevelt, with the result that a "crash program" in atomic research was organized. In 1942 Fermi directed the building of the first nuclear reactor, which produced fission energy in quantity for the first time. In honor of Fermi's work, the United States established the Atomic Energy Commission's Fermi Award for outstanding contributors to the development, the use, or the control of atomic energy. Fermi himself was its first recipient.

UNIT TWO

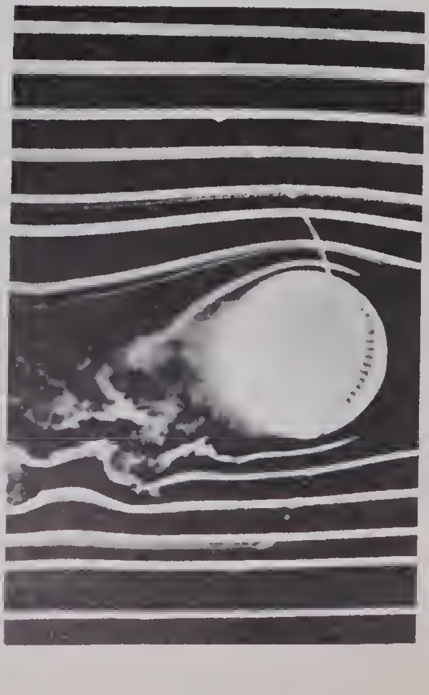
Forces and Machines



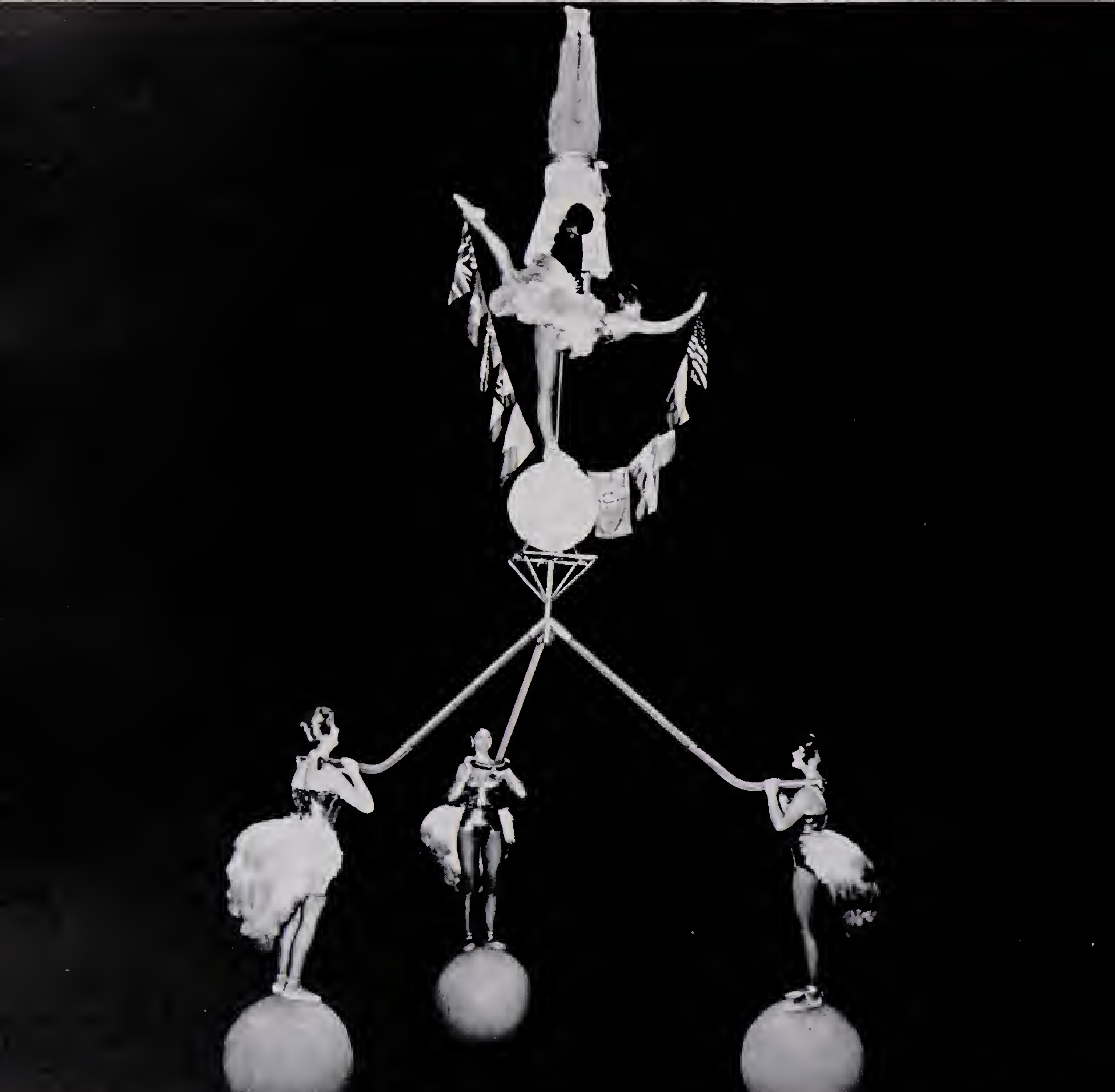
From the DeGolyer copy in the University of Oklahoma Library.

Long ago man learned how to transfer energy through machines to accomplish his work.

By now you have learned some of the fundamental facts about forces and how they produce motions in objects ranging from planets to subatomic particles. Frequently, however, you must be able to analyze situations where there is more than one force and where these forces may be exerted in a variety of directions. In the mechanical tasks of lifting, hauling, and stretching, people use many kinds of machines. In this unit you will study the basic principles of simple machines, and you will learn how they are combined to make complex machines. In addition to forces exerted by solid objects on other solid objects, you will study forces in liquids and gases. Among them are those forces that make baseballs curve and permit birds and airplanes to fly.



CHAPTER 6



Courtesy of Ringling Brothers, Barnum and Bailey Circus.

Circus performers demonstrate forces in equilibrium.

Forces in Equilibrium

Circus people are equilibrium artists. The girls holding bars here are standing on balls that might roll out from under them if they are not careful. By exerting exactly the right forces on the bars, they keep the center bar from moving. If one girl falls down, the pull of the others will put the whole act out of business. Whether they realize it or not, they are giving a fine exhibition of *concurrent forces,* forces which act on a single point. This point is the place where the bars join. Four concurrent forces act here to produce equilibrium: the outward pull of each of the three girls and the downward push of the fourth girl.

The strong man supporting a loaded bar (Fig. 6–2) is demonstrating equilibrium of a different sort. Here the forces are either upward or downward. *Parallel forces* are operating in this case.

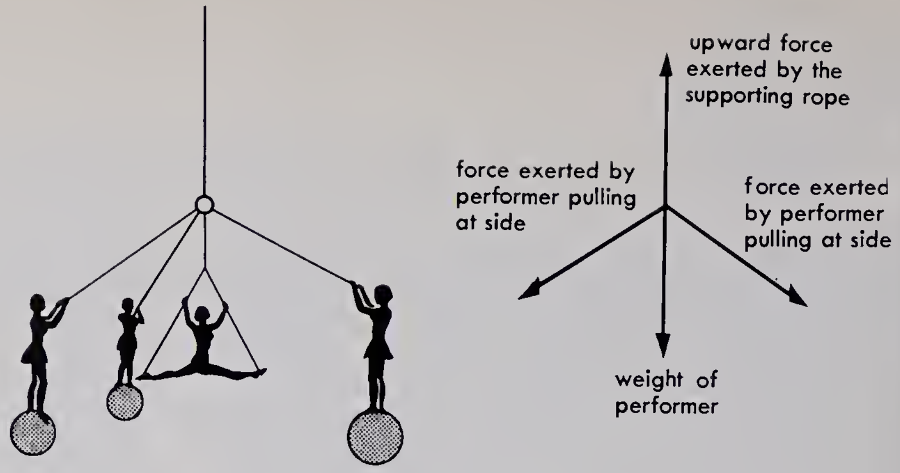
Of course circus performers do not study physics to learn how to produce equilibrium. They learn by trial and error to get the "feel" of a balanced situation, just as a baby learns to keep its balance when walking, or you learn how to stay up on ice skates or how to walk along the top of a fence. A bridge designer, on the other hand, needs a great deal of exact mathematical knowledge about equilibrium to design a bridge such as that in Fig. 6–3 in which concurrent and parallel forces work together to keep the structure safe. In this chapter you will learn about concurrent and parallel forces and about how each type produces equilibrium.

The Resultant of Concurrent Forces

6–1 Vector diagrams represent forces. In Chapter 1 you learned several ways to add velocity vectors. Force vectors can be added in exactly the same way, and the vector sum is again called the resultant. The rules for adding vectors given in Chapter 1 are repeated here:

1. Represent each vector quantity by an arrow with its length and direction representing the magnitude and direction of the vector.
2. If the vectors are in the same or opposite direction, add their numerical values, noting the signs of the vectors.

Figure 6–1 The performers at the right are demonstrating concurrent forces. The vector diagram simplifies the situation by leaving out the performer at the back because it is impossible to make a 3-dimensional vector diagram on a 2-dimensional piece of paper.


upward force exerted by the supporting rope
force exerted by performer pulling at side
force exerted by performer pulling at side
weight of performer

3. If the vectors are at an angle to each other, add them by completing the parallelogram and determining the length and direction of the diagonal drawn from the point at which the bases of the original arrows touch. Do this either by making a scale drawing or by the use of geometry or trigonometry.

You may wish to refresh your mind about how to find a resultant by studying again the problems solved in Figs. 1–1, 1–2, 1–3, and 1–4.

Although concurrent forces act at a point, the point is not always obvious. In Fig. 6–4 the forces are concurrent even though you do not see the wires intersecting. Each of the wires pulls outward and upward on the traffic light, and the mass of earth exerts a gravitational pull downward. In the vector diagram you see that if the arrows representing the forces are extended, they intersect at a single point. The **line of action** of a force may be extended in either direction in order to find out where it crosses other lines of action. Whenever the lines of action of a group of force vectors intersect at a single point, the forces are **concurrent**

Figure 6–2 The strong man exerts two parallel upward forces. These are opposed by the parallel downward forces of the weights of the bar and the people standing on it.

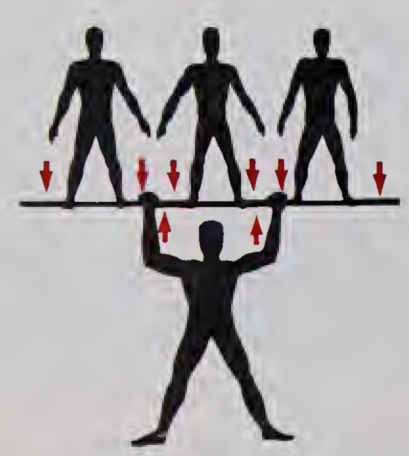


Figure 6-3 The designer of this bridge had to take the effects of many forces into account.

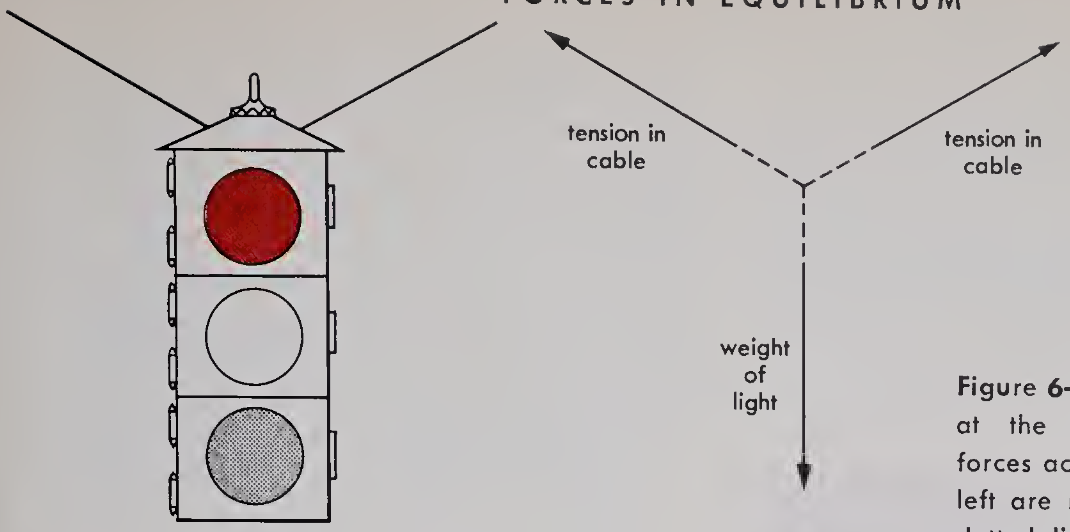


Figure 6–4 The vector diagram at the left shows that the forces acting on the light at the left are really concurrent. The dotted lines show the *lines* of action of the forces.

6–2 Concurrent forces with a resultant of zero produce equilibrium. The airplane in Fig. 6–5 is flying with uniform velocity, that is, with constant speed in a straight line. The four forces acting on the plane are indicated in the diagram. What is the resultant of these forces? The upward lift is exactly equal to the downward gravitational pull of the earth. These add up to zero. The forward thrust is exactly equal to the backward drag. These, too, add up to zero. The resultant of the four forces is zero. There is no unbalanced force acting on the plane and in accordance with Newton's first law, the plane proceeds with uniform velocity.

Concurrent forces acting on an object produce **equilibrium** when their resultant is zero. An object in equilibrium may be moving with uniform velocity, like the plane, or it may be stationary, like the street light of Fig. 6–4 or the bridge of Fig. 6–3.

The resultant is the vector sum of the forces acting, and can be written as

$$\vec{R} = \Sigma\vec{F}$$

where Σ is a symbol meaning "the sum of" and the arrow over the R and the F reminds you that this is a sum of vectors, not just of numbers. For equilibrium, then:

$$\Sigma\vec{F} = 0$$

When F is written without an arrow, only the magnitude of the force is meant.

6–3 The equilibrant is equal to and opposite to the resultant. When you have found the resultant of two or more forces, you have found the single force which, acting alone, could produce exactly the same result as the two or more forces that you

Figure 6–5 In this diagram the forces exerted on a flying airplane are illustrated with vectors. Note that opposite forces are equal and therefore cancel each other. Consequently, the airplane is flying at constant speed.

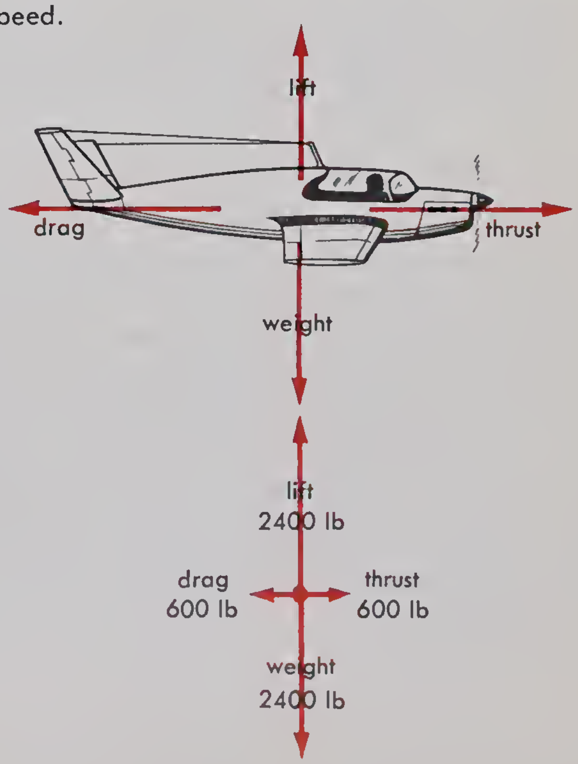
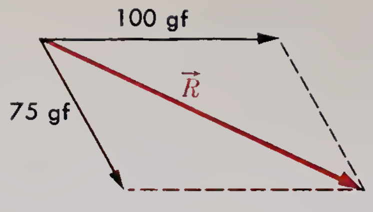
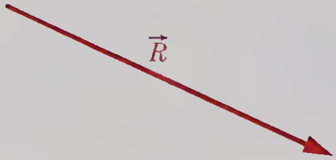


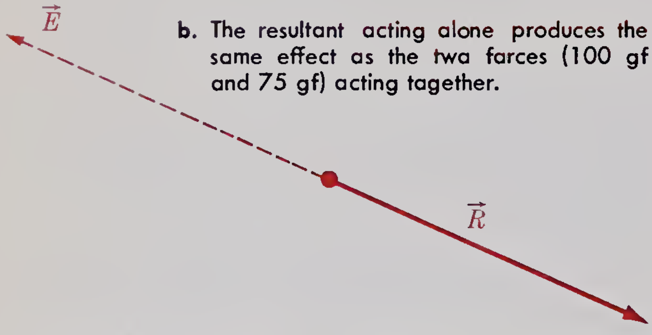
Figure 6–6



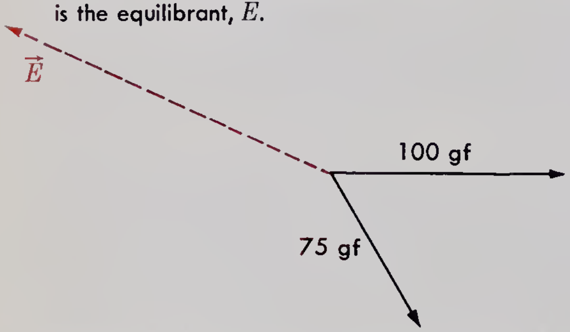
a. The resultant of these two forces is found by completing the parallelogram.



b. The resultant acting alone produces the same effect as the two forces (100 gf and 75 gf) acting together.



c. A force that is equal to the resultant in magnitude, but opposite in direction, will produce equilibrium. This force is the equilibrant, $\vec{E}$.



d. Since the resultant has the same effect alone as the 100 gf and 75 gf forces acting together, the same equilibrant produces equilibrium when it is combined with the two original forces.

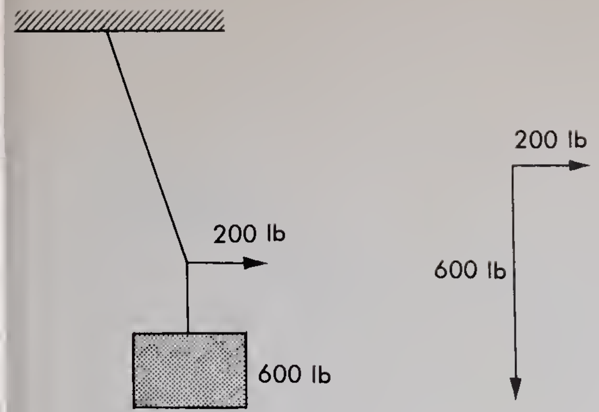
started with. In Fig. 6–6a, the force marked $\vec{R}$ could replace the 100-gf and 75-gf forces, and the result would be the same. In Fig. 6–6b, this single force is shown. The additional force necessary to produce equilibrium is exactly equal in magnitude to $\vec{R}$, but in the opposite direction, as shown in Fig. 6–6c. This **equilibrant**, as it is called, will also produce equilibrium when it acts with the 75-gf and the 100-gf forces, since they have the same effect together as $\vec{R}$ has alone (Fig. 6–6d).

6–4 The equilibrant may be used to solve problems. When several concurrent forces are in equilibrium, any one of them is the equilibrant of the sum (or resultant) of the others. This is useful in solving problems. For example, suppose that a load on a cable is to be pulled aside as shown in Fig. 6–7a on p. 143. The problem is to determine the tension in the supporting cable. To solve this problem, follow these steps:

1. Identify the object on which the forces act. In this case it is the part of the cable to which the horizontal chain is attached.
2. If the forces are concurrent, represent the object on which the forces act by a point; draw the known vectors. If you are solving the problem from a scale drawing, do this very carefully. Otherwise a sketch will do. This step is shown in Fig. 6–7b.
3. Use the diagram to find the unknown quantity. In Fig. 6–7c the resultant is found by completing the parallelogram. Since the load is not moving, after being pulled aside, the forces are in equilibrium and therefore the tension in the supporting cable is the equilibrant of the sum (or resultant) of the other forces.
4. Determine the answer by measurement of the scale drawing or by computation, as shown in Fig. 6–7.

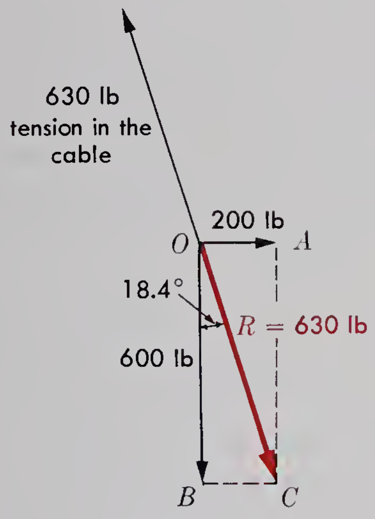
Self Check

1. What is the resultant of a 40-N force due north and a 10-N force due south?
2. What is the equilibrant of two forces toward the east, one of 6 lb and the other of 8 lb?
3. A load is supported by two ropes attached to a ring in the top of the load. Are the forces concurrent?
4. A bridge is supported by vertical pillars. Are the forces on the bridge concurrent?



a. A load on a cable is pulled aside by a force of 200 lb.

b. This is a vector diagram listing the known information.



c. The diagram is completed. The resultant is found either by measuring a scale drawing or by computation. The tension in the cable is equal and opposite to the resultant. Therefore it is 630 lb at an angle of 18.4° with the vertical as shown.

The resultant can be computed from diagram **c** as follows:

$$R^2 = (600\ \text{lb})^2 + (200\ \text{lb})^2$$

$$= 360{,}000\ \text{lb}^2 + 40{,}000\ \text{lb}^2 = 400{,}000\ \text{lb}^2$$

$$R = 630\ \text{lb}$$

$$\tan \angle BOC = \frac{200\ \text{lb}}{600\ \text{lb}} = 0.333$$

$$BOC = 18.4°$$

Figure 6–7 These diagrams show how to find the resultant and equilibrant of two forces.

5. The resultant of a group of forces is a force of 25 kgf directed vertically upward. What is the equilibrant of the forces?
6. The resultant of two forces of 4 lb each is a force of 6 lb. What single force can be added to produce equilibrium?
7. Draw a vector diagram to represent the resultant and equilibrant of a force of 30 N and a force of 40 N at right angles to each other, and compute the values of each.

Problems

For Problems 1–5 (a) find the resultant; (b) state whether or not there will be equilibrium and what kind of motion, if any, the forces produce; (c) find the equilibrant.

A 1. A force of 80 lb upward is exerted on a 70-lb ball.

2. A spring is pulled downward with a force of 30 N. Internal forces in the spring cause an upward pull of 30 N.

3. Two ropes tied to a load make an angle of 120° with each other. Each rope exerts a force of 500 N.

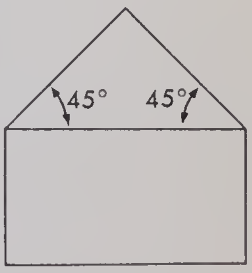
4. A ball is sent upward by a 5.0-lb vertical push. It weighs 2.0 lb and the wind exerts a horizontal push of 1.0 lb.

5. When the 5.0-lb push of Problem 4 no longer acts, what is the resultant?

6. A child in a swing is pulled back by an adult who exerts a horizontal force of 25 lb. If the child weighs 60 lb, what is the tension in each of the two supporting ropes?

7. A speedboat pulls two water skiers at the same time. The ropes held by the skiers make an angle of 90° with each other, and the tension in each rope is 30 kgf. If the boat is moving with uniform speed in a straight line, what force must it be exerting in order to keep the skiers moving. (Note that this does not include the force exerted to keep the boat moving too, just the part of the force necessary to move the skiers.)

8. A 10-lb picture is hung by cords as shown. Find the tension in the cords.

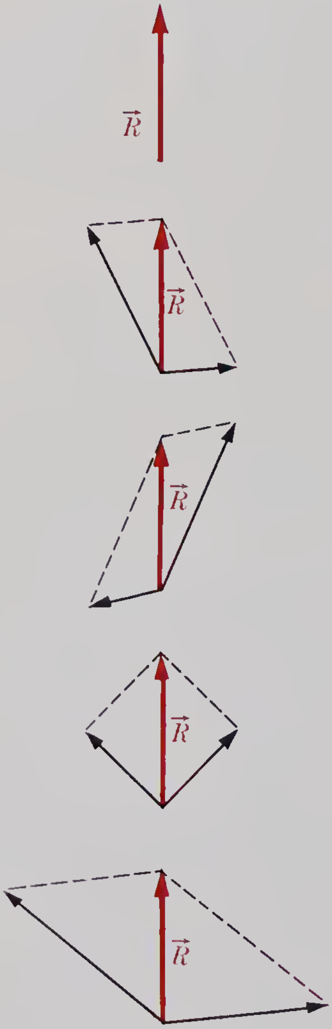


Components of a Force

6–5 A single force may be broken into components. You have seen that two vector forces can be added to find the vector or resultant, $\vec{R}$. The vectors are called the components of $\vec{R}$. They are the forces that, when combined, produce the same effect as $\vec{R}$.

Conversely, a single force can be considered as a resultant produced by a pair of component forces. Knowing the single force, you can find its components, as you learned in Chapter 3 (pages 57–60). And the amazing and delightful fact about components is that you can select them in any direction you wish. In Fig. 6–8 you see a force labeled $\vec{R}$. Each drawing shown below this single force represents a different pair of components of the force $\vec{R}$. There is no limit to the number of such pairs.

Figure 6–8 The force $\vec{R}$, at the top, can be broken into an infinite number of pairs of components. Four possibilities are illustrated here.



The fact that a force may have an infinite number of pairs of components is a very useful one. For example, look at Fig. 6–9. A load of cement is to be transported across a canyon where a dam is being constructed. The weight of the load is known, and so are the angles at which the supporting cables will be stretched. The problem is to find the force of the tension in each cable, so that a strong enough cable can be used.

The vector diagram at the right of Fig. 6–9 shows how this problem can be solved. The weight of the load is a downward force of 15 tons. It is drawn as a vector $\overrightarrow{AB}$. An upward force of 15 tons would just balance this force. It is therefore drawn as the vector $\overrightarrow{AC}$. The components of $\overrightarrow{AC}$, in the directions of the two cables, will be equal to the tensions. Therefore lines of indefinite length, AD and AE, are drawn. Now you can proceed to construct the familiar force parallelogram. This time, since the resultant is known but not the components, you start at the head of the resultant (point C) and construct lines (dotted) parallel to AD and AE. The segments they mark off, $\overrightarrow{AF}$ and $\overrightarrow{AG}$, are the component vectors. Their lengths can be measured to find the tension in each cable. Notice that the tensions are given by the lengths of the vectors in the parallelogram. They are not given by the lengths of the cable. As a matter of fact, when cables supporting a weight are not

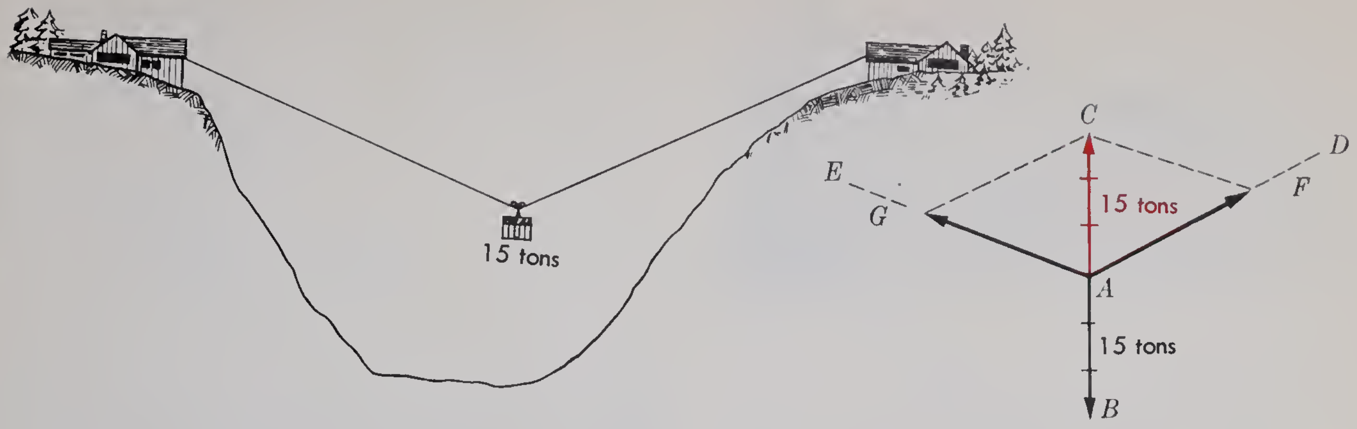


Figure 6–9 The problem here is to compute the tension in each cable. The diagram is set up as at right, with a scale of 1 unit equal to 5 tons. The dotted lines are constructed to form a force parallelogram. This determines the lengths of the vectors $\overrightarrow{AF}$ and $\overrightarrow{AG}$, and from these lengths you can determine their magnitudes. Vector $\overrightarrow{AG}$ represents about 21 tons, while vector $\overrightarrow{AF}$ represents about 22 tons.

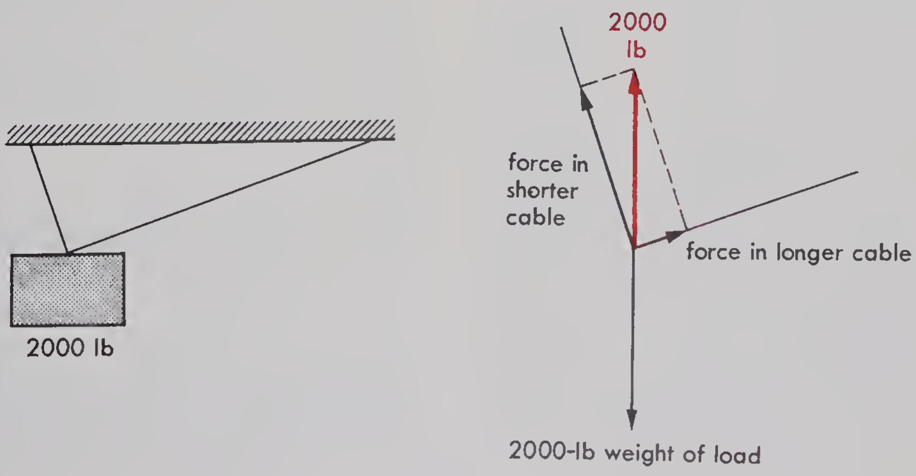
equal in length, the steeper one has the greater tension (Fig. 6–10), and this is often the shorter cable.

The original 15 tons could have been broken up into any one of an infinite number of possible pairs of components. But the problem at hand requires that you choose the pair whose directions correspond to those of the supporting cables.

Thus to find components of a force:

1. Diagram the force and the directions of the two desired components.
2. From the head of the arrow representing the given force, draw lines parallel to the components, thus making a parallelogram of forces.
3. Measure or compute the magnitude of the components.

Figure 6–10 This load is supported by two cables. The more nearly vertical cable supports more of the weight and therefore has the greater tension, even though it is the shorter cable. This fact is illustrated by the vector diagram.



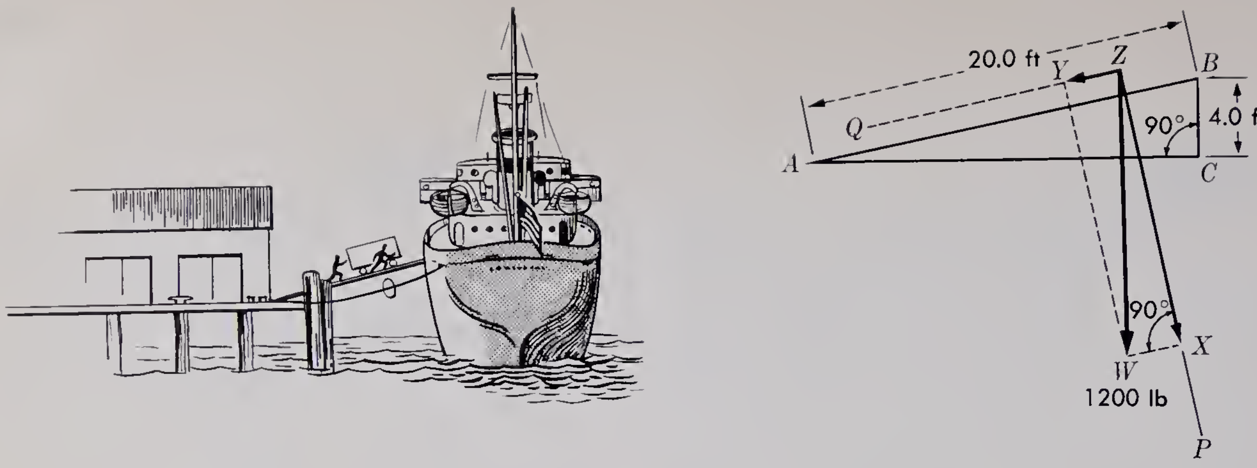


Figure 6–11 In this problem, the weight of 1200 lb is broken up, or analyzed, into two component forces. Here the forces selected are the ones you want to know about — the one which the deck hands must exert (parallel to the ramp) and the one which tends to break the ramp (perpendicular to it.) The solution is mathematical, as shown in the diagram at right and explained in the text.

6–6 Components at right angles may be determined by geometry. Figure 6–11 shows a 1200-lb steel tank being loaded aboard ship. Several men must push it up a ramp from the pier to the deck. Two questions arise: (1) How many men are required if each one can exert 150 lb of force? (2) Will the ramp break? To answer the first question, you must know the force component parallel to the ramp; to answer the second, you must know the force component perpendicular to the ramp. You can answer the questions by finding these components of the 1200-lb load. Assume that the force of friction is so small that it can be neglected.

Now follow the steps listed on p. 145:

1. Draw the ramp to scale (*AB* in Fig. 6–11) and label its length and height, which are 20.0 ft and 4.0 ft. Draw a vector, $\overrightarrow{ZW}$, representing the weight of the tank. It is better not to place Z directly on the ramp, because $\overrightarrow{ZW}$ represents 1200 *pounds* while *AB* represents 20.0 *feet,* and it is better not to get the two kinds of units mixed up. You are interested in the components of $\overrightarrow{ZW}$ parallel to and perpendicular to the slope. Therefore draw two lines of indefinite length, one (*ZQ*) parallel to the slope and the other (*ZP*) perpendicular to it.
2. From the head of the arrow at *W*, draw lines parallel to *ZQ* and *ZP*, completing the parallelogram. $\overrightarrow{ZY}$ and $\overrightarrow{ZX}$ are the two desired components.
3. If you have drawn the diagram carefully to scale, you find that *ZY* is 2.4×10^2 lb and *ZX* is 1.18×10^3 lb. *ZY* is the component of the weight that tends to make the load slide down the ramp. It must be opposed by an equal force supplied by the men. Therefore 2 men will be needed.

This problem can also be solved by geometry. Notice that there are two similar triangles, *ABC,* the ramp triangle, and *ZWX,* the force triangle. You know two sides of the ramp triangle and can easily compute the third one thus:

$$\overline{AB}^2 = \overline{BC}^2 + \overline{AC}^2$$
$$\overline{AC}^2 = \overline{AB}^2 - \overline{BC}^2 = (20.0\text{ ft})^2 - (4.0\text{ ft})^2$$
$$= 400\text{ ft}^2 - 16\text{ ft}^2 = 384\text{ ft}^2$$
$$AC = 19.6\text{ ft}$$

In the force triangle you know that *ZW* is 1200 lb. Since the two triangles are similar, the corresponding sides are proportional.

Therefore:

$$\frac{ZX}{ZW} = \frac{AC}{AB}$$

$$\frac{ZX}{1200\text{ lb}} = \frac{19.6\text{ ft}}{20.0\text{ ft}}$$

$$ZX = \frac{19.6 \times 1200\text{ lb}}{20.0} = 1.18 \times 10^3\text{ lb}$$

This is the force that tends to break the ramp. The force required to pull the tank up the ramp can be determined in a similar manner.

$$\frac{ZY}{ZW} = \frac{BC}{AB}$$

$$\frac{ZY}{1200\text{ lb}} = \frac{4.0\text{ ft}}{20.0\text{ ft}}$$

$$ZY = \frac{4.0 \times 1200\text{ lb}}{20.0} = 2.4 \times 10^2\text{ lb}$$

Self Check

1. Draw a vector representing a force of 100 N at an angle of 30° with the horizontal, and show its vertical and horizontal components.
2. Draw a vector representing a force of 100 N at an angle of 30° with the horizontal, and show the components of this force along a slope at an angle of 20° with the horizontal and perpendicular to this slope.
3. Draw a vector representing a vertical force of 100 N, and show the components of this force along a slope at an angle of 30° with the horizontal and perpendicular to this slope.
4. How many pairs of components can be drawn for a single force?
5. What is the vertical component of a vertical force of 10 N?
6. What is the horizontal component of a vertical force of 10 N?
7. What is the difference between ZW and $\overrightarrow{ZW}$?

Problems

A 1. The light in Fig. 6–4 weighs 50 lb and the cables make an angle of 30° with the horizontal. What is the tension in each cable?

2. A 100-kgf load hangs from the end of a boom as shown in Fig. 6–12. Find the pull (tension) of the chain and the push (compression) of the boom on the point from which the load is suspended.

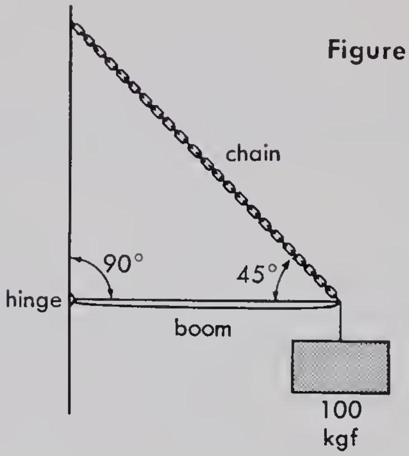
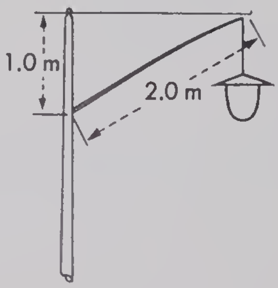


Figure 6–12

3. A car weighs 2500 lb. What force must be supplied to send it up a slope that rises 5.00 ft for every 100 ft along the slope? With what force does the car press on the road? Assume that forces of friction and air resistance are too small to matter.

4. A street light is supported as shown in the diagram. If the light weighs 4 kgf, what are the forces in the two rods from which the light hangs? Forces in the rigid vertical post are not considered in this problem. When you make your force diagram, ask yourself whether the rod you are considering is pushing or pulling on the point from which the light hangs. If this is a hard question to decide, then ask whether a chain could be substituted for the rod. If the answer is "yes" then the force is a pull; if the answer is "no" then the force is a push.



Discussion Questions

1. Which is more likely to break, a clothesline pulled tight, or one that sags? Why?
2. Suspension bridges like that in Fig. 6–3 have high towers and large amount of dip in the cables. Why is this preferred to lower towers and straighter cables?
3. Which is harder to push, a lawn mower with a short handle, or one with a long handle? Why?

Using Trigonometry in Force Problems

Often the simplest way to solve problems involving forces is by the use of trigonometry.

6–7 Trigonometry can be used to find components. Suppose that a 2000-lb car is traveling at a uniform 50 mi/hr on a level road. This is an equilibrium situation, with the forward force equalling the backward forces of friction and air resistance. Now the road starts to rise at an angle of 15.0°. What additional force is required to keep the car at a speed of 50 mi/hr?

To solve this problem, start by making a sketch of the situation with the given information (Fig. 6–13a). Then, following the procedure you have learned:

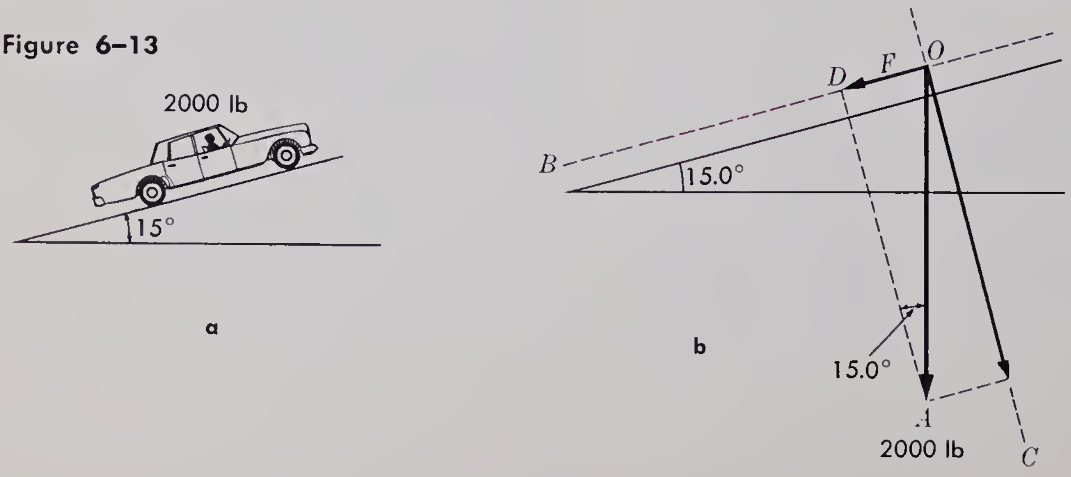
1. Represent the car by a point and draw a vector representing its weight ($\overrightarrow{OA}$ in Fig. 6–13b). You are interested in finding the component of this force in the direction of the slope. Therefore you draw two lines of indefinite length, one (OB) parallel to the slope and one (OC) perpendicular to it.
2. Starting from the head of the arrow at A, complete the parallelogram which, in this case, is a rectangle. The vector, $\vec{F}$, is the component of the weight of the car that acts down the slope. If the car is to climb the hill, an extra force equal to F must be supplied. In the triangle OAD, the angle at A is the same as the angle of the slope, so it has been marked 15.0°.
3. Now use the diagram to find the unknown force, F. The triangle OAD is a right triangle. You know that the angle at A is 15.0° and that the hypotenuse is 2000 lb. You wish to find the value of the side opposite the 15.0° angle. This suggests that you use the sine of the angle:

$$\frac{\text{side opposite}}{\text{hypotenuse}} = \sin A$$

$$\frac{F}{2000\text{ lb}} = \sin 15.0^\circ = 0.259$$

$$F = 518\text{ lb}$$

Figure 6–13



a

b

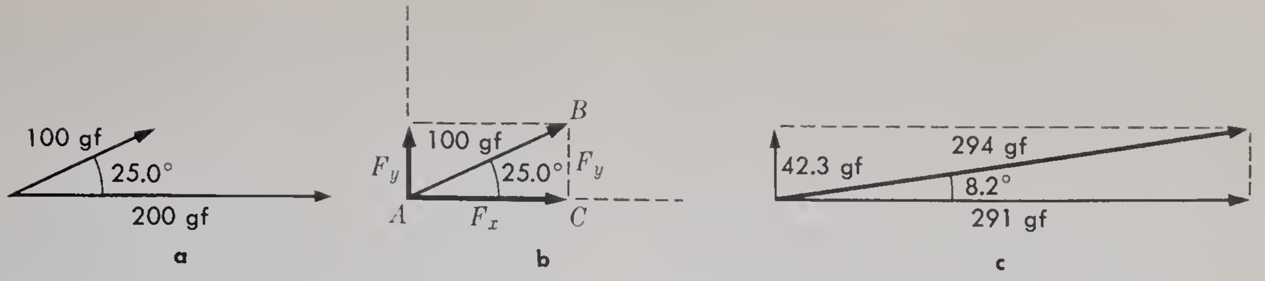


Figure 6–14 Trigonometric functions are used here to find a resultant. The method is explained in the text.

6–8 Trigonometry can be used to find the resultant. A force of 100 gf acts at an angle of 25.0° from a force of 200 gf. The problem is to find the magnitude and direction of the resultant.

First make a diagram to show the conditions of the problem (Fig. 6–14a). If you solve this problem by trigonometry, do not make a parallelogram with these two forces. Instead find two components of the 100-gf force, one in the direction of the 200-gf force, and one perpendicular to it (Fig. 6–14b). These components have been labelled F_x (horizontal force) and F_y (vertical force). Since opposite sides of the rectangle are equal, BC is also equal to F_y. In the triangle ABC:

$$\frac{F_y}{100 \text{ gf}} = \sin 25.0° = 0.423$$

$$F_y = 42.3 \text{ gf}$$

$$\frac{F_x}{100 \text{ gf}} = \cos 25.0° = 0.906$$

$$F_x = 90.6 \text{ gf}$$

The 200-gf force is horizontal and so has no vertical component.

Now, in combining the two original forces given, the sum of the horizontal components must be the horizontal component of the resultant, and the sum of the vertical components must be the vertical component of the resultant. These components are added in the next column.

Force	*Horizontal* Component	*Vertical* Component
100 gf	91 gf	42.3 gf
200 gf	200 gf	0
Resultant	291 gf	42.3 gf

These totals can be represented in a new parallelogram (Fig. 6–14c). Since this is a rectangle, you can use the geometry of the triangle to find the resultant:

$$\begin{aligned} R^2 &= (42.3 \text{ gf})^2 + (291 \text{ gf})^2 \\ &= 1790 \text{ gf}^2 + 84{,}700 \text{ gf}^2 \\ &= 8.65 \times 10^4 \text{ gf}^2 \\ R &= 294 \text{ gf} \end{aligned}$$

Notice that in the solution of this problem, the results were rounded off to three figures. This is because the information given was accurate to three significant digits and therefore you are not justified in recording more. Next you can use your knowledge of the tangent of an angle to find the angle of the resultant:

$$\tan A = \frac{42.3 \text{ gf}}{291 \text{ gf}} = 0.145$$

$$A = 8.2°$$

Can you see that this method is superior to the graphical solution you learned before? Can you see how it can be used to find the resultant of three or more concurrent forces?

6–9 Trigonometry may be used in equilibrium problems. The airplane in Fig. 6–5 (p. 141) is in equilibrium because the resultant of all the forces acting on it is zero. You check this by adding the vertical forces:

$$2400 \text{ lb (lift)} - 2400 \text{ lb (weight)} = 0$$

and then by adding the horizontal forces:

$$600 \text{ lb (thrust)} - 600 \text{ lb (drag)} = 0$$

For an object to be in equilibrium, the sum of the components of the forces in any direction must be zero. In the case of the airplane, horizontal and vertical components were added, with upward vectors and those to the right being called positive, and downward ones and those to the left, negative. Horizontal and vertical components are usually (but not always) used in force problems, so the equilibrium law is often written as:

$$\textit{For equilibrium:} \quad \Sigma F_x = 0 \qquad \Sigma F_y = 0$$

Remember that the symbol Σ means "the sum of," F_x means horizontal forces, and F_y means vertical forces.

To see how useful trigonometry can be in solving an equilibrium problem, consider the situation in Fig. 6–15. A lamp is hung in the middle of the street by cables attached to the roofs of buildings of unequal height; the angles are 35.0° and 25.0°. The lamp weighs 100 lb. The problem is to find the tension in each of the cables.

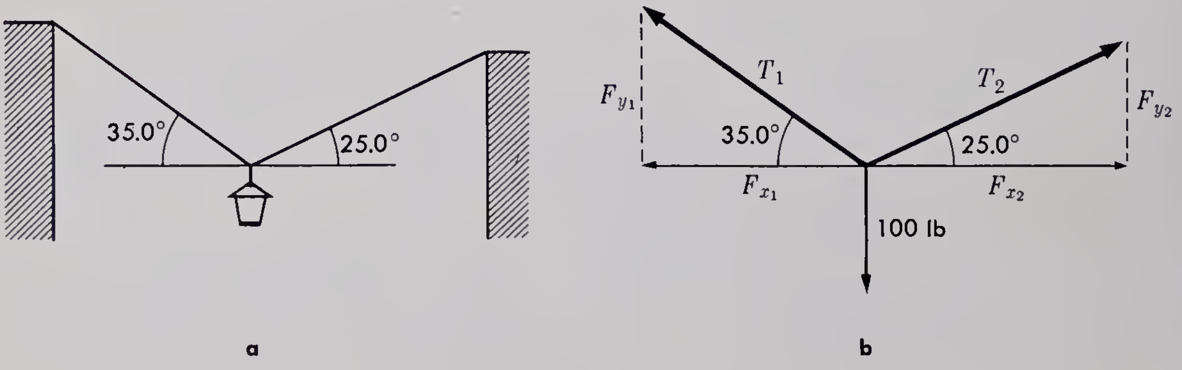
1. Identify the object on which the forces act. In this case, it is the point where the two cables and the support of the lamp join.
2. Represent the object by a point, since the forces are concurrent, and make a vector diagram of the given information (Fig. 6–15b).
3. Complete the diagram and label unknown quantities to be found. Since the solution is to be obtained by trigonometry, a sketch rather than a scale drawing is good enough. The tensions in the cables, $\vec{T}_1$ and $\vec{T}_2$, are indicated at any convenient length, and no parallelogram is necessary because this problem is to be solved by using components, which are shown in the drawing.
4. Determine the answer by computation. Set up equations, using the equilibrium law. Since the only force known is a vertical one, start with $\Sigma F_y = 0$. The vertical component of T_1 is labeled F_{y_1}.

$$\frac{F_{y_1}}{T_1} = \sin 35.0°$$

$$F_{y_1} = T_1 \sin 35.0°$$

The vertical component of T_2 is found in the same way to be $T_2 \sin 25.0°$. Both of these components are directed up and therefore carry a positive sign; the weight

Figure 6–15 Trigonometric functions are used here to solve an equilibrium problem. The method is explained in the text.



is directed down and carries a negative sign. Therefore:

$$\begin{aligned} \Sigma F_y &= 0 \\ T_1 \sin 35.0^\circ + T_2 \sin 25.0^\circ - 100\ \text{lb} &= 0 \\ 0.574T_1 + 0.423T_2 - 100\ \text{lb} &= 0 \end{aligned}$$

This equation has two unknowns and so cannot be solved. However, similar computations for the horizontal components will give the other equation required.

The horizontal component of T_1 is found as follows:

$$\frac{F_{x_1}}{T_1} = \cos 35.0^\circ$$

$$F_{x_1} = T_1 \cos 35.0^\circ$$

The horizontal component of T_2 is found in the same way to be $T_2 \cos 25.0^\circ$.

$$\begin{aligned} \Sigma F_x &= 0 \\ T_2 \cos 25.0^\circ - T_1 \cos 35.0^\circ &= 0 \\ 0.906T_2 - 0.819T_1 &= 0 \end{aligned}$$

Therefore

$$T_2 = \frac{0.819}{0.906} T_1$$

This can be substituted in the previous equation:

$$\begin{aligned} 0.574T_1 + 0.423 \times \frac{0.819}{0.906} T_1 &= 100\ \text{lb} \\ 0.574T_1 + 0.382T_1 &= 100\ \text{lb} \\ 0.956T_1 &= 100\ \text{lb} \\ T_1 &= 104\ \text{lb} \end{aligned}$$

$$T_2 = \frac{0.819}{0.906} \times 104\ \text{lb} = 94.0\ \text{lb}$$

Self Check

1. Write trigonometric expressions for the components you drew in answer to Questions 1, 2, and 3 of the Self Check on p. 147. Do not solve.

Three forces have vertical and horizontal components as shown:

Force	Vertical component	Horizontal component
A	20 lb	5 lb
B	20 lb	25 lb
C	15 lb	15 lb

2. Which force makes an angle of more than 45° with the horizontal?
3. Which force makes an angle of 45° with the horizontal?
4. What is the horizontal component of the resultant of these forces?
5. What is the vertical component of the resultant of these forces?
6. Write a mathematical expression from which you could compute the magnitude of the resultant.
7. Write a trigonometric expression from which you could find the direction of the resultant.

Problems

Ⓐ **1.** Solve Problem 8, p. 143, using trigonometry.

2. A picture 4.0 ft wide and 3.0 ft high weighs 6.0 kgf. The supporting wires make an angle of 10° with the horizontal. What must be the minimum strength of the wires?

3. Find the resultant of forces of 50 N at an angle of 25° with the horizontal and 80 N at an angle of 70° with the horizontal, both angles being measured counterclockwise from a horizontal reference line that runs toward the right.

Ⓑ **4.** Find the resultant of the following forces, all measured counterclockwise from a horizontal reference line that runs toward the right; 100 gf at 20.0°; 200 gf at 120.0°; 100 gf at 330.0°.

Parallel Forces

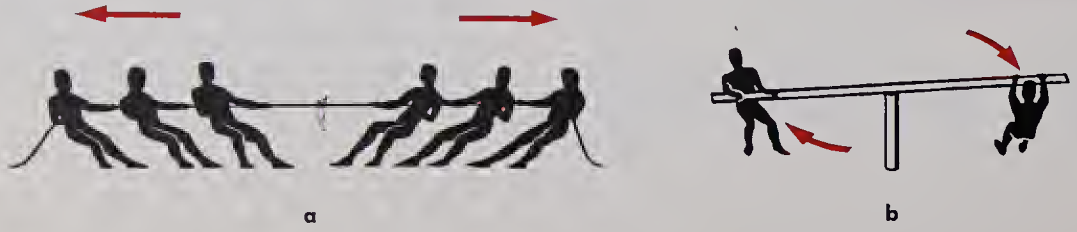
If two teams engage in a tug of war, and both pull with a force of 400 lb (Fig. 6–16a), the two forces balance each other and there is equilibrium. If, however, instead of pulling on opposite ends of a rope, the two teams were to pull on opposite ends of a long board pivoted at the middle, as shown in Fig. 6–16b, even though the two forces are still equal, there would not be equilibrium. The board would rotate. In the first case the forces are equal in magnitude, opposite in direction, and concurrent. In the second case, although the forces are still equal in magnitude and opposite in direction, they are not concurrent. They are parallel. Equilibrium with parallel forces involves more than merely providing a force resultant that is equal to zero.

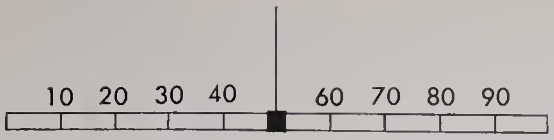
6–10 Children on a seesaw learn how to balance parallel forces. If two children have about the same weight, they can balance if they sit near opposite ends of the board. If a heavy child and a light child sit on opposite ends, however, the heavy one pulls his end down and the light one stays up in the air. To make the seesaw balance, the heavy child moves in toward the center. Apparently equilibrium with parallel forces involves not only the size and direction of the force, but also its distance from a center of rotation.

Here is a simple experiment to show how equilibrium is produced with parallel forces. Suspend a meter stick as shown in Fig. 6–17, and hang weights from it. Four different arrangements (b, d, e, and f) that result in equilibrium are shown. The weights to the right of the center tend to cause the stick to rotate in a clockwise direction, while those on the left tend to cause it to rotate in a counterclockwise direction. In order to make clear the rule that governs the balancing, the information from the experiment can be put in the form of a chart:

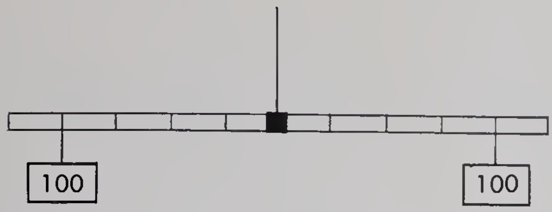
Kind of Rotation	Force (F) gf	Distance from center (L) cm	$F \times L$ gf · cm
	Fig. 6–17b		
Counterclockwise	100	40	4000
Clockwise	100	40	4000
	Fig. 6–17d		
Counterclockwise	100	20	2000
Clockwise	50	40	2000
	Fig. 6–17e		
Counterclockwise	100	10	1000
Clockwise	25	40	1000
	Fig. 6–17f		
Counterclockwise	100	20	2000
Clockwise	50	20	1000
Clockwise	25	40	1000
			2000

Figure 6–16

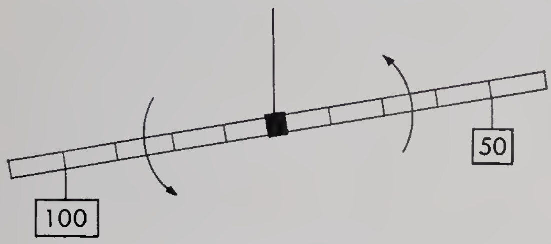




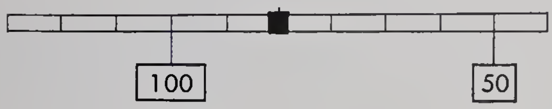
a. The meter stick is suspended so that it balances. Thus its weight does not affect the rotation.



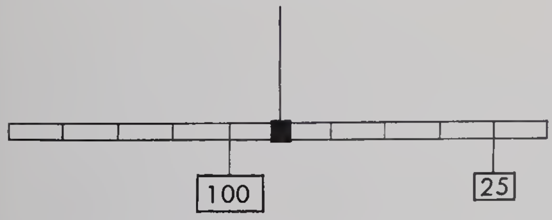
b. When two 100-gf weights are hung 40 cm from the center, one to the right and one to the left, the stick balances.



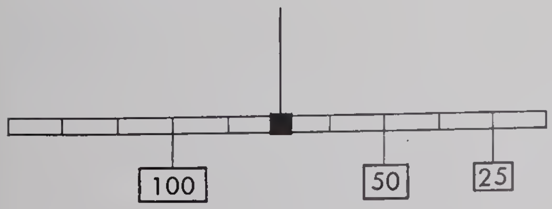
c. When the 100-gf weight on the right is replaced by a 50-gf weight, the stick rotates in a counterclockwise direction.



d. The stick balances again if the 100-gf weight is moved halfway in, so that it is 20 cm from the center.



e. The stick also balances when a 25-gf weight is hung 40 cm from the center and a 100-gf weight is 10 cm from the center, on the other side.



f. This is a more complicated situation. The stick will balance when the weights are hung as shown.

Figure 6–17 The law of moments.

In the last column of the chart the force has been multiplied by the distance from the center of rotation. Notice that in each equilibrium arrangement, $F \times L$ for clockwise turning is equal to $F \times L$ for counterclockwise turning. The product of the magnitude of the force and the perpendicular distance from the center of rotation to the line of action of the force is called the **moment** (or **torque**) of the force. The distance is called the **lever arm** or **moment arm**. The moment of a force is a measure of its effectiveness in causing rotation. The formula for the moment (M) of a force is:

$$M = FL$$

where F is the force and L is the lever arm.

Notice the kinds of units that you get for the moment of a force. If the force is in newtons and the lever arm in meters, the unit will be the newton meter. This sounds like the unit of work called the joule, but it is not. In the case of work, the force and the distance are in the same direction. In the case of a moment, they are at right angles to each other. The unit of work and the unit of moment of force are therefore not the same thing, although their names sound alike. You may say that the moment of a force is 20 newton · meters, for example, but you may never say it is 20 joules. The joule is always a work unit.

6–11 Equilibrium laws apply to parallel forces. Look again at the meter stick of Fig. 6–17. Two downward forces are acting, but the meter stick does not fall to the ground. This is because the support is supplying an upward force equal to the sum of the two downward forces. This upward force is 100 gf + 50 gf, or 150 gf. The equilibrium law for concurrent forces also applies here:

$$\Sigma \vec{F} = 0$$

In addition, as you saw with all the examples of Fig. 6–17, when parallel forces

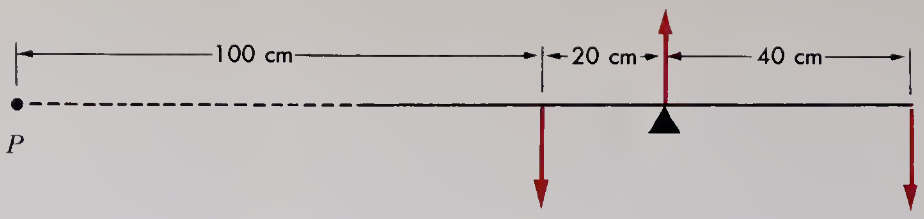


Figure 6–18 This force diagram illustrates the situation of Fig. 6–17d.

produce equilibrium, the sum of the clockwise moments equals the sum of the counterclockwise moments. This is called the **law of moments,** and can be written as:

$$\Sigma M \text{ (clockwise)} = \Sigma M \text{ (counterclockwise).}$$

Some people prefer to think of the clockwise moments as positive and the counterclockwise ones as negative. Then they write the law of moments as:

$$\Sigma M = 0$$

These laws apply no matter where you put the center of rotation. Figure 6–18 illustrates the force diagram for the meter stick of Fig. 6–17d. Here it is natural to think of the point of support as the center of rotation. This point has been marked with a triangle and is usually called the **fulcrum.** Around this point the 50-gf force tends to cause a clockwise rotation and the 100-gf force tends to cause a counterclockwise rotation. If you use these figures in the law of moments you have:

$$50 \text{ gf} \times 40 \text{ cm} = 100 \text{ gf} \times 20 \text{ cm}$$
$$2.0 \times 10^3 \text{ gf} \cdot \text{cm} = 2.0 \times 10^3 \text{ gf} \cdot \text{cm}$$

Now suppose you take the point from which the 50-gf weight is hung as the fulcrum. Around this point the 150-gf force tends to cause a clockwise rotation, while the 100-gf force tends to cause a counterclockwise rotation. The 50-gf force can cause no rotation about this point, because it runs through the point and has a 0 lever arm. The law of moments equation is:

$$150 \text{ gf} \times 40 \text{ cm} = 100 \text{ gf} \times 60 \text{ cm}$$
$$6.0 \times 10^3 \text{ gf} \cdot \text{cm} = 6.0 \times 10^3 \text{ gf} \cdot \text{cm}$$

Again the law checks.

You can even take an imaginary point for the fulcrum, one that is not even on the meter stick. Such a point is *P* in Fig. 6–18, 100 cm away from the 100-gf force. Around this point the moments of the 100-gf and 50-gf forces are clockwise and that of the 150-gf force is counterclockwise.

$$100 \text{ gf} \times 100 \text{ cm} + 50 \text{ gf} \times 160 \text{ cm} = 150 \text{ gf} \times 120 \text{ cm}$$

$$10.0 \times 10^3 \text{ gf} \cdot \text{cm} + 8.0 \times 10^3 \text{ gf} \cdot \text{cm} = 18.0 \times 10^3 \text{ gf} \cdot \text{cm}$$
$$18.0 \times 10^3 \text{ gf} \cdot \text{cm} = 18.0 \times 10^3 \text{ gf} \cdot \text{cm}$$

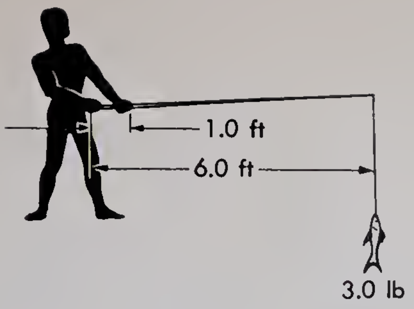
Again the law checks.

When you solve a problem involving moments, use any convenient point for the fulcrum. Then check the accuracy of your answer by using some other point of rotation.

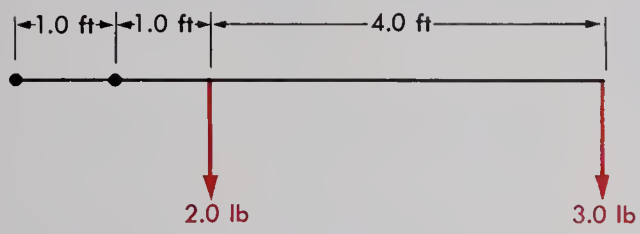
The steps in solving a problem involving forces that are not concurrent are shown in Fig. 6–19. They are very similar to the steps given on p. 150 for concurrent forces.

6–12 The lever arm is not always obvious. If you wish to open a door, you usually pull straight out on the knob. If you reach over to pull the door at an angle other than 90°, you find that it is more difficult to open the door. This is because you have shortened the lever arm and therefore need a greater force to produce the same moment. Figure 6–20 illustrates this fact. The lever arm is the perpendicular distance from the point of rotation to the line along which the force acts. Sometimes you have to extend the line of action of the force in order to draw the lever arm.

The law of moments applies even when



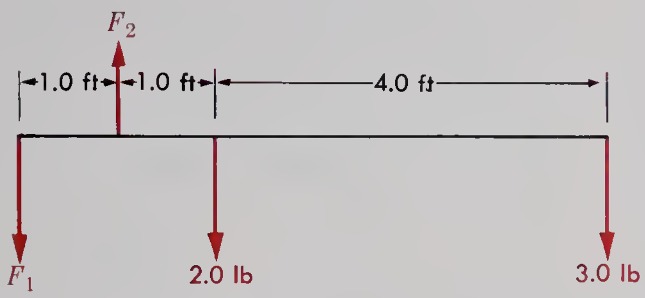
A man holds a 6.0 ft pole horizontally with both hands, one at the end and the other hand 1.0 ft from the end. He has just caught a 3.0 lb fish. The pole weighs 2.0 lb and you can consider its weight to be concentrated 2.0 ft from the end near the man's hands. What is the force exerted by each hand?



The solution of this problem follows the steps given on p. 142, with a modification to take care of the fact that the forces are not concurrent.

1. Identify the object on which the forces act. In this case it is the fish pole.

2. If the forces are concurrent, the object is represented by a point. Here the forces are not concurrent, so the object is represented by a line with the distances marked out and the known forces listed.



3. Complete the diagram and label unknown quantities to be found. Remember that the forces act on *the pole*, not on the hands or on the fish. The hand on the end of the pole pushes down on the pole. The hand 1.0 ft from the end pulls up on the pole.

4. Determine the answer by computation. Taking moments around the left end (the center of rotation must be identified in your solution):

$$F_2 \times 1.0\text{ ft} = 2.0\text{ lb} \times 2.0\text{ ft} + 3.0\text{ lb} \times 6.0\text{ ft} = 22\text{ lb·ft}\cdot$$

$$F_2 = 22\text{ lb},\ \textit{Answer}$$

$$\Sigma \vec{F} = 0$$

$$F_2 - F_1 - 2.0\text{ lb} - 3.0\text{ lb} = 0$$

$$22\text{ lb} - F_1 - 5.0\text{ lb} = 0$$

$$F_1 = 17\text{ lb},\ \textit{Answer}$$

Check the problem by taking moments around the right end or some other suitable points:

$$F_2 \times 5.0\text{ ft} = F_1 \times 6.0\text{ ft} + 2.0\text{ lb} \times 4.0\text{ ft}$$

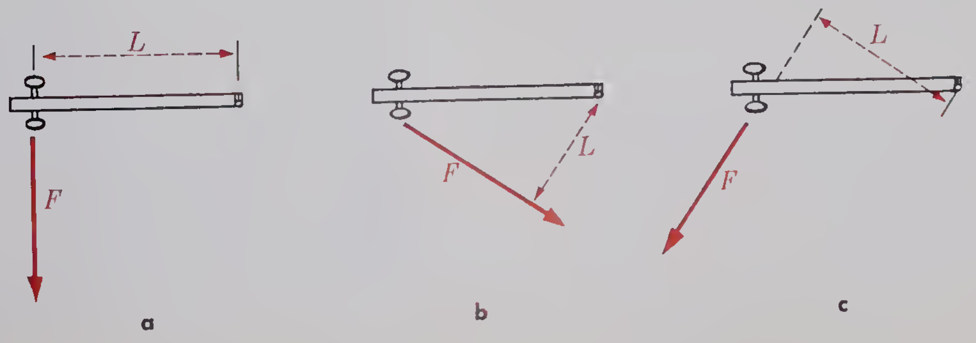
$$22\text{ lb} \times 5.0\text{ ft} = 17\text{ lb} \times 6.0\text{ ft} + 8.0\text{ lb·ft}$$

$$110\text{ lb·ft} = 102\text{ lb·ft} + 8\text{ lb·ft}$$

$$110\text{ lb·ft} = 110\text{ lb·ft},\ \textit{Check}$$

Figure 6–19 How to solve a problem when the forces are not concurrent.

Figure 6–20 The manner in which the length of a lever arm changes when the angle of the force changes is shown here. These are drawings of a door as seen from above with the hinge at the right and the knob at the left. In each case, L is the lever arm. Notice that L is not always the distance along the door from the hinge to the knob. Instead, it is the perpendicular distance from the hinge to the line along which the force acts. In **b** and **c** the force must be greater than in **a** to produce the same torque, because L is smaller.



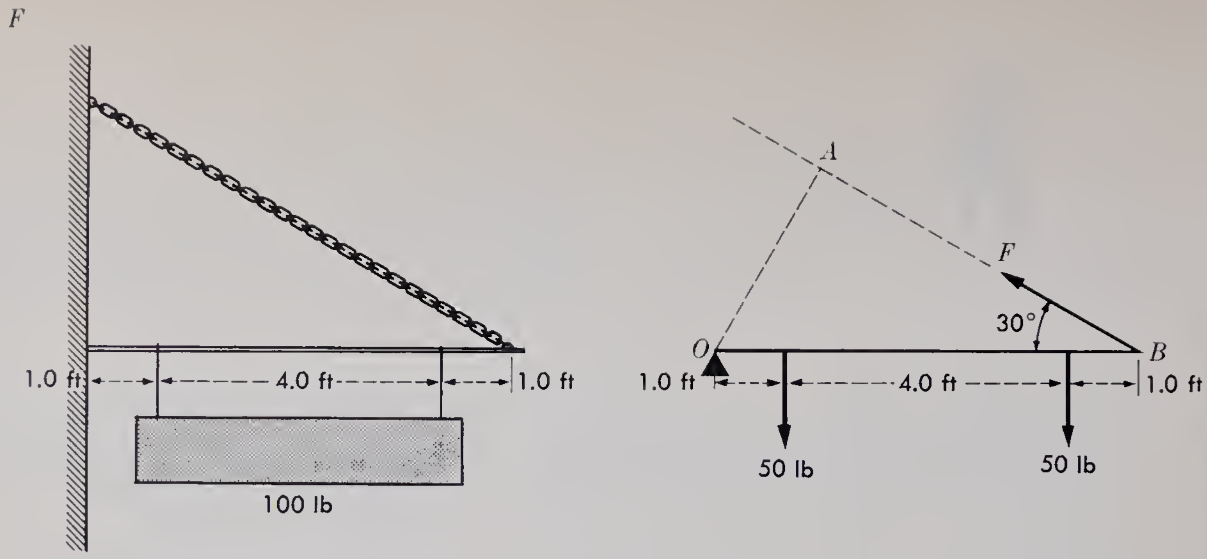
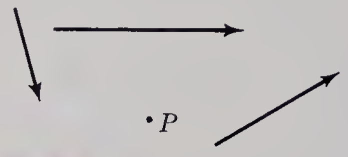


Figure 6–21

the forces are not parallel. Figure 6–21 shows a sign with the supports that hold it up. The diagram at the right shows the forces acting on the horizontal rod. If you want to use the law of moments to find the force in the chain, you need to know the lever arms. The lever arms for the two 50-lb forces, taking the left-hand end as the fulcrum, are 1 ft and 5 ft. The lever arm for the force in the chain is the distance *OA*.

Self Check

1. A 20-lb weight is hung on the end of a horizontal pole 10 ft long. What is the moment of the force around the other end of the pole?
2. What is the moment of the force of Question 1 around the center of the pole?
3. What is another name for moment?
4. Define the lever arm of a force.
5. If moments acting on an object are not balanced, what is the result?
6. State in words the two equilibrium laws for parallel forces.
7. State the two equilibrium laws for parallel forces in mathematical form.
8. Which produces a greater moment, a force of 10 N with a lever arm of 3 m or a force of 8 N with a lever arm of 4 m?
9. What additional moment will produce equilibrium if a clockwise force of 3 lb at 2 ft from a fulcrum is opposed by a counterclockwise force of 4 lb at 1 ft from a fulcrum?
10. Copy this drawing and show the lever arms of the forces around the indicated point *P*.



Problems

Every time you write an equation, tell where you have put the point of rotation.

A 1. Check the law of moments in Fig. 6–17f by taking moments around the point where the 100-gf force is attached.

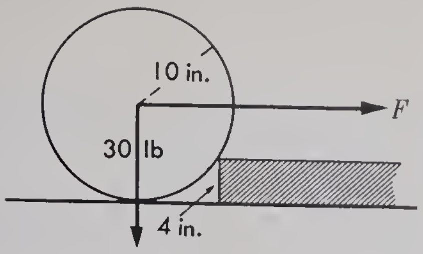
2. A 200-gf weight is hung at the 10-cm mark on a meter stick which is suspended at the 50-cm mark. Where will a 500-gf weight have to be hung to balance it?

3. Two men carry a 300-lb load by hanging it from a horizontal pole that rests on one shoulder of each man. If the men are 10.0 ft apart and the load is 4.0 ft from one of them, how much load does each man support? Assume that the weight of the pole is negligible. (Hint: Your algebra will be simpler if you take the fulcrum at a shoulder.)

4. A meter stick is suspended at the center and a 200-gf weight is hung at the 20-cm mark. An unknown weight just balances the system when it is hung at the 90-cm mark. What is the unknown weight?

B 5. What is the force in the chain of Fig. 6–21?

Figure 6–22



6. There is a fourth force, not drawn in Fig. 6–21, which also acts on the horizontal rod (not the weight of the rod, for that is negligible). Where does this force act? Use $\Sigma F_x = 0$ and $\Sigma F_y = 0$ to find the magnitude and direction of this force.

7. A wheel weighing 30 lb is pulled horizontally (Fig. 6–22). What force is just sufficient to turn it so that it will rise over the curb? What happens to the size of this force as the wheel rises?

Discussion Questions

1. Why is it easier to open a door if you pull straight out instead of pulling at an angle?
2. You are trying to put a screw eye into a board with your fingers. How could you make the work easier?
3. Can two concurrent forces produce equilibrium? Explain.
4. Can two parallel forces that are not concurrent produce equilibrium? Explain.
5. Can three concurrent forces produce equilibrium? Can three parallel nonconcurrent forces produce equilibrium? Explain.

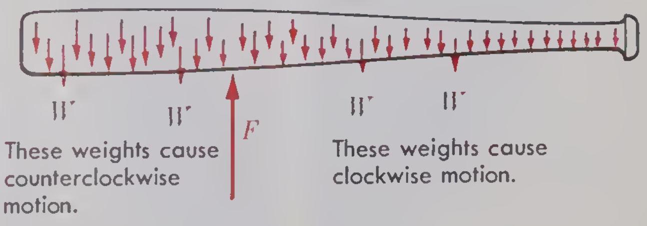
The Center of Gravity

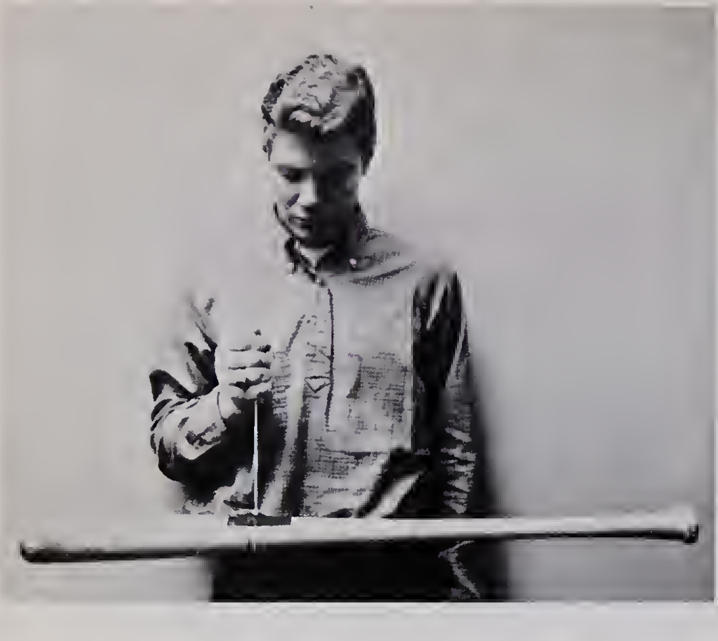
6–13 Objects balance at the center of gravity. The boy in Fig. 6–23 is balancing a baseball bat on one finger. If you try to do this, you discover that there is only one spot along the length of the bat where you can make it balance. This spot is near the thicker end. If you hold your finger anywhere else, the bat rotates and falls off your finger. You know that rotation is caused by unbalanced moments. When you have your finger in the right place, the moments in the two directions are equal.

Figure 6–23 To balance the bat, the boy must support it near its thicker end.

An object such as this bat is composed of many tiny atoms, each being attracted by the pull of the earth. This is illustrated in Fig. 6–24, where a few of the weight vectors are shown. The position of the boy's finger is shown by the large arrow. He supports the bat with a force equal to the sum

Figure 6–24 Each atom in the bat is pulled downward by a force W (its weight.) The bat is in equilibrium when the upward force, F, exerted by the boy's finger is equal to the sum of the weights of all of the atoms, and when the clockwise moments equal the counterclockwise moments.


W
W
F
W
W
These weights cause counterclockwise motion.
These weights cause clockwise motion.



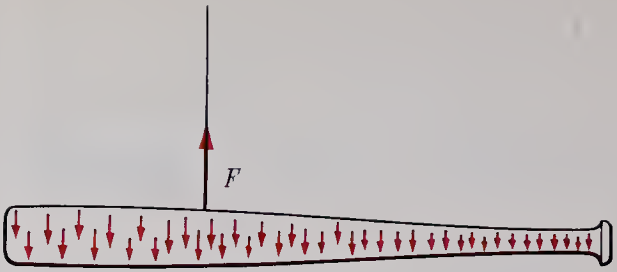


Figure 6–25 The bat is supported by a single force directly above its center of gravity.

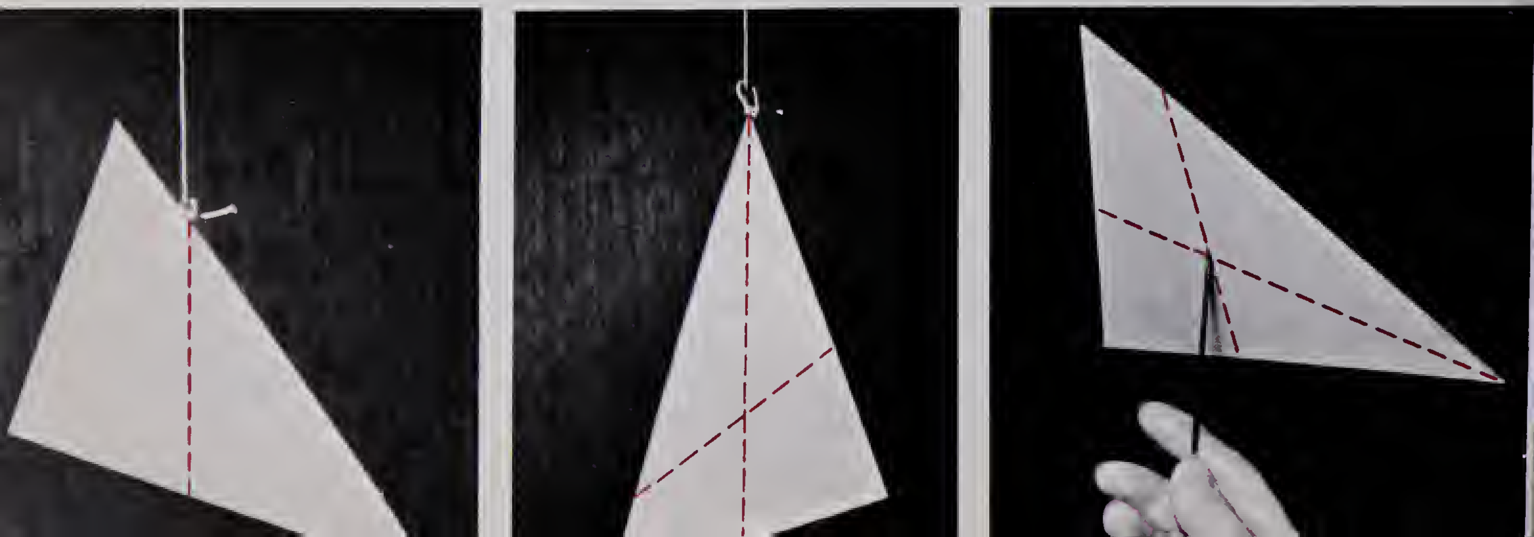
of all of the weights of the atoms. In addition, each of the atoms exerts a moment because of its weight and position. The bat balances when the boy puts his finger at the spot around which the sum of the clockwise moments equals the sum of the counterclockwise moments. His finger is then directly under the center of gravity.

If the boy now tapes a looped cord to the bat at the point where his finger supported it, he can suspend the bat from above. Again it will balance (Fig. 6–25). This time the support is directly above the center of gravity. When an object is supported by a single force, the line of action of the force goes through the center of gravity of the object.

This fact makes it possible to find the center of gravity of any flat object, regular or irregular (Fig. 6–26). First the object, a cardboard triangle in this case, is suspended as shown at the left. The center of gravity lies directly below the support, along the line of action of the supporting force (dotted line). Then the triangle is suspended from another point. Now the center of gravity lies along the dashed line. Since the center of gravity lies on both the dotted and dashed lines, you know that it is at the intersection of the two lines as shown.

If an object is suspended or pivoted from its center of gravity, it will balance perfectly. You can test this by making a small hole through the triangle, as shown in Fig. 6–26c. Then if the triangle is supported by a pin through the hole, you can turn it into any position and it will balance there and

Figure 6–26 These pictures show how the center of gravity of a flat triangular object may be found. Then one upward force at that point produces equilibrium (balance).



not rotate. If you spin it around the pin, it will move smoothly and evenly, without jolting.

6–14 Weight may be considered to be concentrated at the center of gravity. Figure 6–27a is a vector diagram representing the weights of some of the atoms of the triangle of Fig. 6–26. These are balanced by the upward force of the support. This upward force is equal to the sum of the downward forces and produces equilibrium if it acts through the center of gravity. You would also get equilibrium if you substituted for all of the small weights of the atoms a single downward weight acting through the center of gravity, as shown in Fig. 6–27b. This downward force has been labeled $\vec{R}$ because it is the resultant of the small weights. The size and direction of the resultant is determined by adding all the force vectors. The point through which it acts is determined by the moments of the forces. The **center of gravity** can thus be defined as the *point of action* of the resultant of the weights of the individual particles in the object. Because of this, you can solve problems involving moments by assuming that the entire weight of the body is concentrated at its center of gravity. This was done in the fishpole problem (Fig. 6–19).

6–15 The center of gravity may be outside the object. It is quite reasonable to expect that the center of gravity of a solid ball is at its geometrical center. But suppose the ball is hollow. The only point around which the moments due to the weights of the atoms in the ball would balance is still the geometrical center, even though none of the mass of the ball is there. You may think it even stranger that the center of gravity of a doughnut is in the middle of the hole, but this is indeed the case.

6–16 Stability depends on the center of gravity. From experience you know that some objects are less apt to tip over than others. Thus a brick set on its long side is less likely to tip over than one set on its end. If you attempt to balance a pencil on its point, it tips over. On the other hand, a cylinder on its side or a ball cannot tip over no matter how it is disturbed. This ability to resist being tipped over is known as **mechanical stability**. You can understand and predict stability easily if you apply the concept of center of gravity.

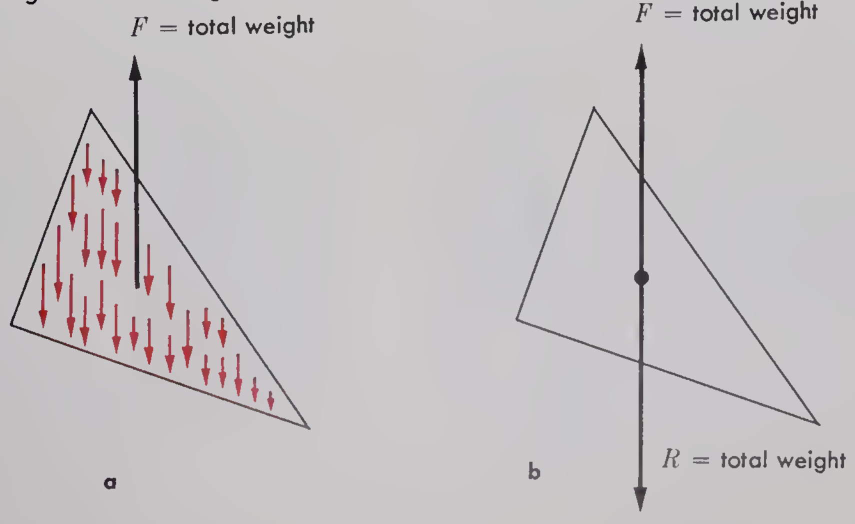


Figure 6–27 In a the triangle balances because the upward force equals the sum of the downward forces, and because, when it is supported at its center of gravity, the moments in the two directions are equal, thus creating a net moment equal to zero. In b the triangle would also balance if all its weight were concentrated at the center of gravity. A downward force equal to the total weight, acting at the center of gravity, is the resultant ($\overrightarrow{R}$) of all the forces acting on the triangle.

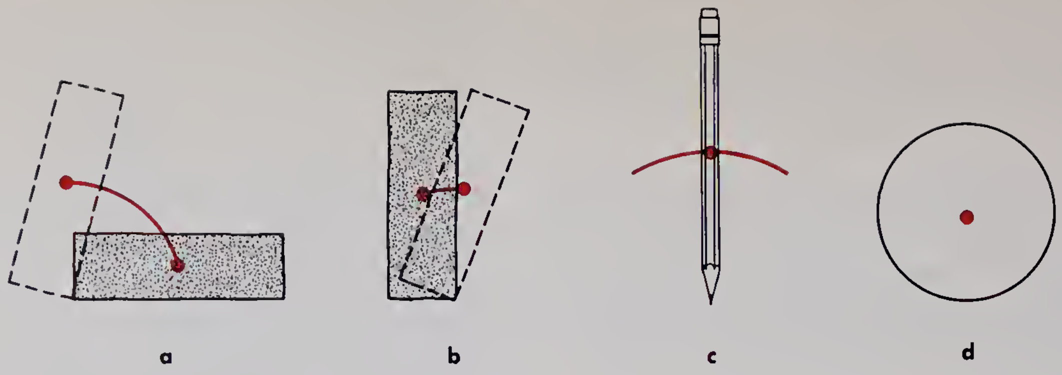
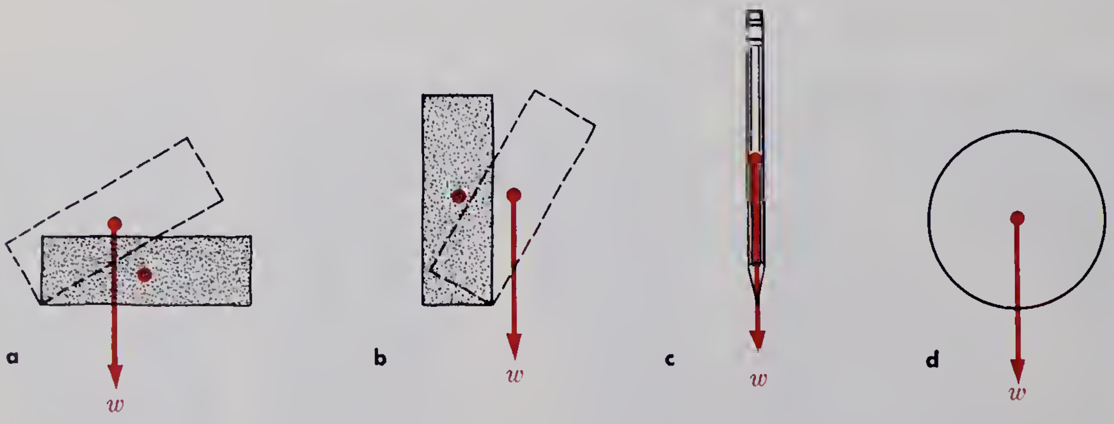


Figure 6–28 The stability of an object depends upon the location of the center of gravity.

In Fig. 6–28, the center of gravity is shown as a heavy dot within each of the objects. In the case of the brick on its long side, the illustration shows that the center of gravity must be raised a relatively great distance when the brick is tipped. This means that the object resists upsetting, that it is very stable. The brick on its end is less stable because its center of gravity need not be lifted so far before the brick is tipped over. The shape of the pencil is such that the center of gravity need not be raised at all in order for the object to tip over. But no matter how the ball is tipped, its center of gravity is neither raised nor lowered. As a result, the ball neither tends to tip nor to roll, nor does it resist tipping or rolling.

Stability can be thought of in terms of the moments caused by the weight of the object. Figure 6–29 shows the same objects with the weight indicated as a vector acting at the center of gravity. When the brick on its long side is tipped slightly, the weight causes a moment around the supporting edge that makes the brick fall back to its original position. On the other hand, if you tip the up-ended brick by the same angle, the weight causes a moment that forces the brick to continue to rotate and thus to fall. This is also true with the pencil. The weight of the ball always acts on a line through its point of support; therefore the weight of the ball can never produce a moment.

Figure 6–29 An object tips over whenever the weight, considered to be concentrated at the center of gravity, causes a moment that tips it. When the brick in **a** is raised, the moment tends to restore it to its original position. The moment in **b** causes the brick to fall. No matter how small the amount of tipping in **c**, the moment causes the pencil to fall, since it is balanced on a narrow point. The moment in **d** is always zero.



Self Check

1. If you stand on one leg, where must your center of gravity be if you are not to fall down?
2. If you hang by one hand from a stationary trapeze, where is your center of gravity?
3. If you know where the center of gravity of an object is located, what assumption can you make that is useful in problem solving?
4. If you take the center of gravity of an object as the point of rotation, what is the sum of the moments due to the weights of the individual atoms of the object?
5. Where is the center of gravity of an unmounted automobile tire?
6. A rod is brass at one end and wood at the other. For ease in balancing it on end, which end should be down?

Problems

Ⓐ **1.** A meter stick weighing 150 gf is suspended from the 40.0-cm mark. If the center of gravity of the stick is at the 50.0-cm mark, where will a 200-gf weight have to be placed to produce equilibrium?

2. A 3.00-ton truck has a wheelbase (distance from front axle to back axle) of 14.00 ft. If the center of gravity of the truck when empty is 6.00 ft from the front axle, how much weight is supported by each wheel?

3. A 5.00-ton load is put on the truck of Problem 2. If the center of gravity of the load is 4.00 ft from the rear axle, what is now the weight supported by each wheel?

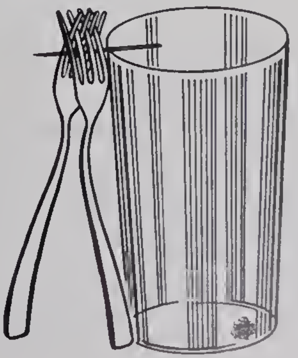


Figure 6–30

Discussion Questions

1. Put two dinner forks together as shown in Fig. 6–30. Support them on a toothpick over the rim of a glass so that neither of the forks touches the glass. Burn the part of the toothpick that is inside the glass. The forks will balance on the tiny support that is left and can even be pushed gently so that they sway without falling off. Why?
2. A man balances on his two hands with his feet in the air. Then he lifts his right hand off of the floor and stands on the left one alone. How will his body shift?
3. Examine a beam balance in the laboratory before answering this one. Suppose the beam has been moved slightly to the right, so that it is no longer supported where it should be. You put an object in the right-hand pan to be weighed, and you put brass weights into the left-hand pan until they balance. Will you measure the correct weight of the object? Why?

Chapter Summary

Concurrent forces are those whose lines of action intersect at a single point. They produce equilibrium when the vector sum of the forces is zero. A group of concurrent unbalanced forces may be brought into equilibrium by a force equal and opposite to the resultant. This force is called the equilibrant. A single force may be considered to be made up of any one pair of an infinite number of pairs of components. Components, resultants, and equilibrants can be determined by scale drawings, by geometry, or by trigonometry.

Unbalanced parallel forces cause rotation. The effectiveness of a force in causing rotation is its moment, or torque, which is the product of the force and the perpendicular distance from the point of rotation to the line of action of the force. Nonconcurrent forces in the same plane produce equilibrium when the vector sum of the forces is zero and when the sum of the clockwise moments equals the sum of the counterclockwise moments. The entire weight of an object may be assumed to act at its center of gravity. Around this point the moments due to the weights of all of the particles of mass in the object add up to zero. The location of the center of gravity and the geometry of the base determines the stability of an object. The lower the center of gravity of an object, the more difficult it is to tip it over.

Vocabulary

concurrent forces (*p. 139*)
parallel forces (*p. 139*)
line of action of a force (*p. 140*)
equilibrium (*p. 141*)
equilibrant (*p. 142*)
component (*p. 144*)
moment (*p. 153*)
torque (*p. 153*)
lever arm (*p. 153*)
law of moments (*p. 154*)
fulcrum (*p. 154*)
point of rotation (*p. 154*)
nonconcurrent forces (*p. 154*)
center of gravity (*p. 159*)
mechanical stability (*p. 159*)

Problems

A 1. Find the resultant and equilibrant in each of the following: (a) 60 gf up; 20 gf down; 5 gf up. (b) 10 tons north; 30 tons east; 10 tons south. (c) 50 N up; 10 N horizontally to the right; 20 N horizontally to the left; 40 N down.

2. A weight of 50 kgf hangs from a 5.0-m rope and is pulled aside 3.0-m by a horizontal force. Find the horizontal force and the tension in the rope. Draw separate diagrams of the hanging weight and of the concurrent forces.

3. Write the two equations of equilibrium for the situation shown in Fig. 6–12 and solve.

4. A weight of 300 lb is suspended as shown in Fig. 6–31. Find the tensions in the supporting cables.

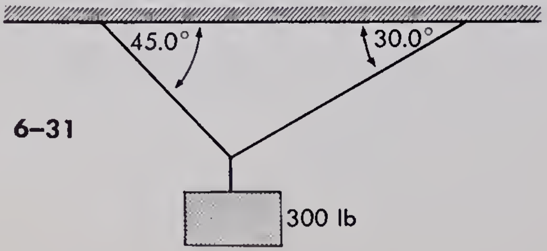


Figure 6–31

5. A plank 5.0 m long is used as a footbridge across a brook. The plank is uniform and weighs 40 kgf. A boy weighing 60 kgf stands on the bridge 3.0 m from one end. With what force is the plank supported at each end?

6. A two-wheeled boat trailer plus a boat weigh 1600 lb. The center of gravity of boat and trailer is 2.00 ft in front of the axle, the axle being 8.00 ft from the ball hitch on the rear of the towing car. Then a 500-lb motor is put on the rear of the boat at a distance of 12 ft from the hitch. Find the force on the axle and on the hitch. (You may have trouble deciding the direction of the force on the hitch. If you guess wrong, your answer will come out with a negative sign in front of it.)

B 7. A boom like that in Fig. 6–12 weighs 50.0 kgf and is 20.0 m long. The chain makes an angle of 30° with the boom and the load at the end is 200 kgf. What is the tension in the chain?

Discussion Questions

1. Attach a rope to the leg of a heavy chair and try to pull the chair. Now attach the free end of the rope tightly to a radiator or other firmly fixed object. Push down on the rope, or lift it straight up. Compare the force necessary to move the chair in the two cases and explain. How could you apply this experiment to the problem of pulling a car out of the mud when no tow truck is available?
2. Which strains your arms most, hanging with your hands close together on an overhead bar, or with your hands spread apart? Why?
3. A board supported at both ends will break if loaded with 350 lb at the middle. However, if it is used at an angle of 30° to load a 400-lb crate onto a truck, it does not break. Explain.
4. Why are doorknobs put as far away from the hinge side of a door as possible?
5. Why is it easier to unscrew a wide-headed bolt with your fingers than a narrow-headed one?
6. Under what circumstances can an object in equilibrium be moving?

PHYSICS HALL OF FAME

Archimedes · c. 287–212 B.C.

"Give me a place to stand and I will move the earth!" Does this seem like an extravagant claim to you? Consider, however, that the man who may have spoken these words had discovered the principle of the lever. What he meant by his boast was that with a long enough lever (and a fixed place to use as a fulcrum) he could raise the weight of the earth. — An exaggeration, but Archimedes' confidence was justifiable, for the lever has turned out to be one of the most useful of all simple machines.

Probably the most famous of the many legends about Archimedes is that of the king's gold crown. Archimedes lived in the Greek colony of Syracuse, in Sicily, and was a close friend of Hieron, the king of Syracuse. Hieron had given a goldsmith a certain weight of gold with which to make a crown. He suspected, however, that the goldsmith might have used an equal weight of a gold and silver mixture, keeping the leftover gold for himself. Hieron asked Archimedes to test the quality of the gold without destroying the crown. According to the legend, Archimedes was pondering the problem one day at the public baths. As he stepped into a full tub and noticed the water spilling over, a solution suddenly came to him. He leaped out of the tub and, without bothering to dress, ran home to try his idea, shouting "Eureka!" ("I've found it!") as he ran. The cause for his elation was this: He had realized that just as his body displaced water from the tub, so might he determine the volume of the king's crown by seeing how much water it would displace from a full container. Since silver is less dense than gold, he knew that a crown made of gold and silver would displace more water than an equal weight of pure gold. Thus he would be able to expose the goldsmith's possible fraud.

Although Archimedes was one of the greatest mechanical inventors of all time, he prided himself only on his work as a mathematician. One of his greatest mathematical achievements was the geometric development of certain ideas related to modern calculus, a branch of mathematics widely used in physics today.

CHAPTER 7

Courtesy of the Solomon R. Guggenheim Museum, New York City.

A view from the top of the Guggenheim Museum in New York City shows a long, spiral ramp. Although it may not look like one, this ramp is a simple machine.

Force and Simple Machines

When you think of machines, you may have in mind a factory room full of metal monsters with turning wheels and thumping parts. Or you may think of a bulldozer pushing tons of earth. Perhaps you think of airplanes and diesel locomotives (Fig. 7–1). Machines, very complicated ones, are built into these devices. But would you include the ramp in the picture opposite or the objects in Fig. 7–2 in a list of machines? You should — because that is just what they are.

With a machine you can do work more easily or more quickly. With an egg beater you can whip up eggs faster than with a fork. Try pounding a nail with the head of a hammer held in your hand. This is a difficult task. With a handle on that hammer it is easy. The complex machines of Fig. 7–1 are made by fitting together many simple machines, as simple as those of Fig. 7–2.

When a machine is used to do work, some energy is always wasted because of friction. In order to understand how machines operate, you need to know something about friction, a force that has its uses as well as its disadvantages.

In this chapter you will learn how the force of friction is used and controlled and how simple machines are used to do work.

The Force of Friction

7–1 Friction is common in daily life. Friction is so common in daily life that you usually take it for granted. A coasting wagon or bicycle or automobile slows down because of friction with the road. Even when you skate or slide on ice, some friction is present, though it is relatively slight. However, you would find it very difficult to slide on a bare sidewalk, because the friction between your shoe soles and the pavement would be too great. When you apply the brakes of an automobile, it stops because of friction between the tires and the road, and also between the brake linings and the brake drums. In fact, friction exists between all moving surfaces, whether they are in automobiles, washing machines, brooms, or pencil erasers. There is even friction between a moving object and the air through which it moves; this is called **air resistance**

Sometimes friction is very useful. You

Figure 7–1 These are complex machines.

have already seen that brakes on moving vehicles operate because of friction. Similarly, without friction between the tires and the road automobiles would not move. You could not run or walk if there were no friction between your feet and the floor. Without friction, dishes and furniture and other objects about the house would move at the slightest touch. So you see that friction is not something that must always be eliminated or even reduced. Many times it is desirable to increase friction.

7–2 Friction exists between surfaces. What makes a door squeak when you open it slowly? If you open the same door very quickly, it may not squeak at all. Why? Why will a door stop squeaking when the hinges are oiled? The answers to these three questions contain much of what is known about friction.

If you write on a blackboard with the chalk held in the usual way, you draw a smooth line. But if you hold it so that the writing end of the chalk moves ahead of your hand, you may find that the chalk jumps along so that it makes a series of dots. First it sticks to the board, then it slips, then it sticks again. Scientists call this behavior stick-slip. When one surface moves past another, it often does so with a stick-slip. The stick-slip of a door hinge causes the vibration you hear as a squeak. Figure 7–3 is an enlargement of the surface of a metal, showing the irregularities caused by stick-slip when the metal was cut.

Scientists formerly believed that the sticking was due to roughness, with the bumps of one surface getting tangled with the bumps of the other. Most scientists today who have studied friction believe that the major cause is the attraction of the ma-

Figure 7–2 These are simple machines.

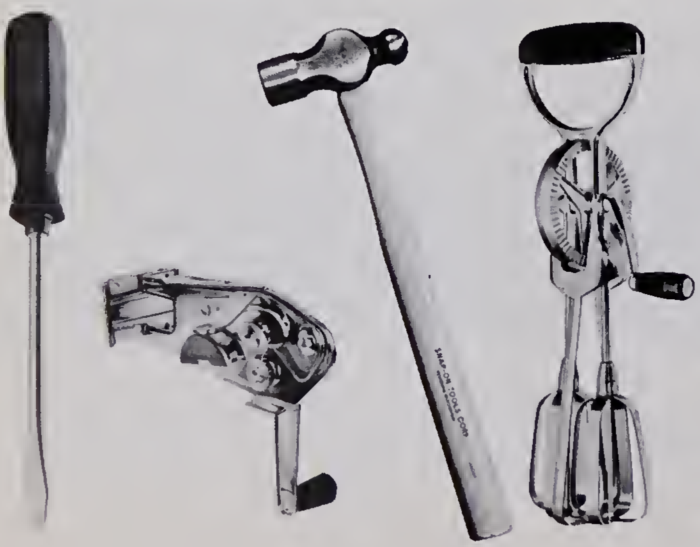
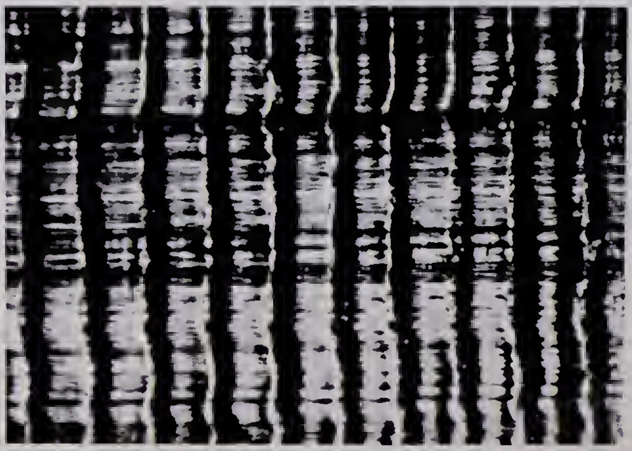


Figure 7–3 A photograph of the surface of titanium metal cut by a blade which was sticking and slipping.



terials of the two surfaces for each other, although the bumps on the surfaces also play a part. The attraction is much greater when the two surfaces are very close together. For this reason, the friction of sliding surfaces increases as they are forced closer and closer together. The force of attraction that causes friction is not gravitational. That would be too small a force to account for the size of the force of friction. Scientists believe it is largely electrical. The **force of friction** may be defined as a force that opposes the motion of one surface over another, because of the attraction of the surfaces for each other, or because of the irregularities of the surfaces, or both.

What is the direction of the force of friction? If you push a heavy crate over a wooden floor, you push in the direction of the motion in order to overcome the force of friction. This shows that the direction of the force of friction is opposed to the direction of the motion. If you get on the other side of the crate and push it back to its original location, the direction of the force of friction is also reversed. Its direction is again opposed to the direction of the motion.

7–3 The force of friction depends on certain factors. A few simple experiments tell much about the way in which friction acts.

The force of friction is directly proportional to the force pressing the two surfaces together. In Fig. 7–4 a brick is placed on a table and pulled by a string. The reading of the spring balance attached to the string indicates the force necessary to overcome friction when the brick is moving along the floor at constant speed. This is equal in magnitude to the force of friction, but opposite to it in direction. When a single brick is pulled, the force is 400 gf. If a second brick is placed on top of the first, the force goes up to 800 gf; with a load

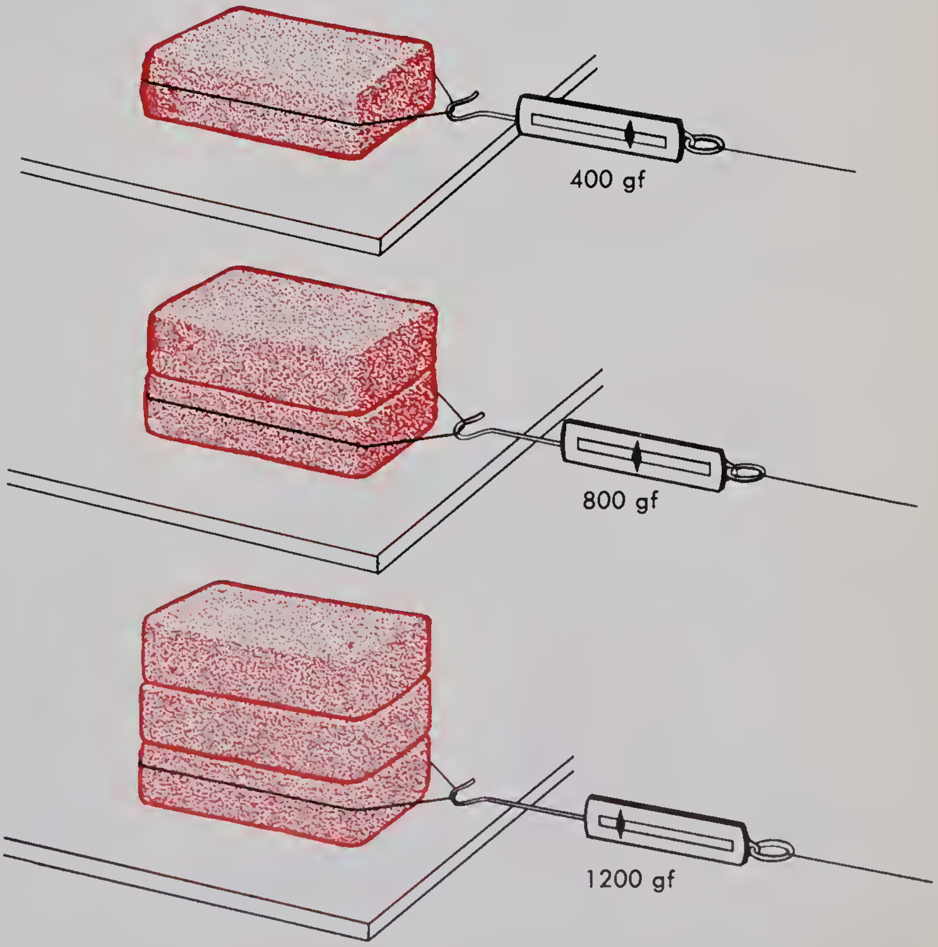


Figure 7–4 This experiment indicates that frictional force is directly proportional to the force pressing the two surfaces together.

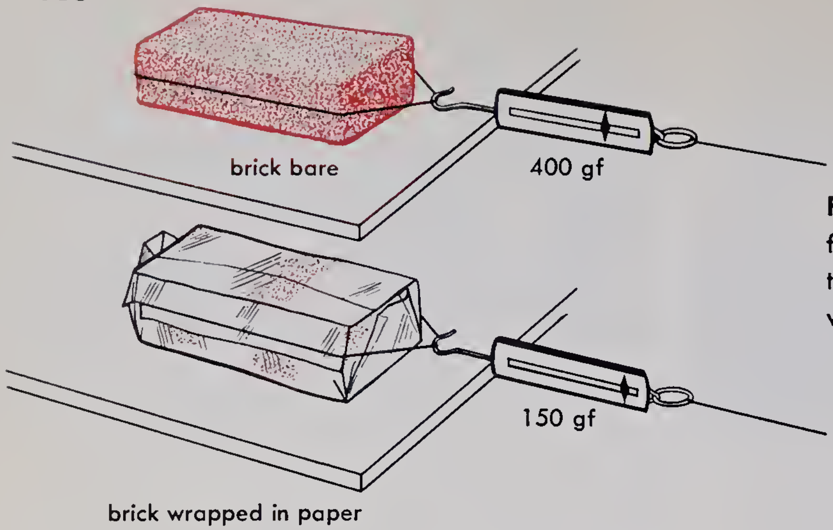


Figure 7–5 This experiment indicates that frictional force depends, among other things, on the nature of the surfaces involved.

of three bricks, the force is 1200 gf. This shows that the frictional force is directly proportional to the force pressing the two surfaces together.

The force of friction depends on the nature of the surfaces involved. When the brick is wrapped in paper, as shown in Fig. 7–5, the force of friction is less than with the bare brick. This suggests that sliding friction may be controlled by proper selection of the surfaces.

Other things being equal, the force of friction is independent of area. The experiment of Fig. 7–6 is designed to see whether area has anything to do with the force of friction. Whether the brick slides on its side, edge, or end, the force is the same. Other things being equal, frictional force is independent of area. In many cases, of course, other things are not equal. If a sharp object digs into a surface over which it is sliding, friction does increase.

The force of friction depends on the kind of motion of the surfaces. When the ten-

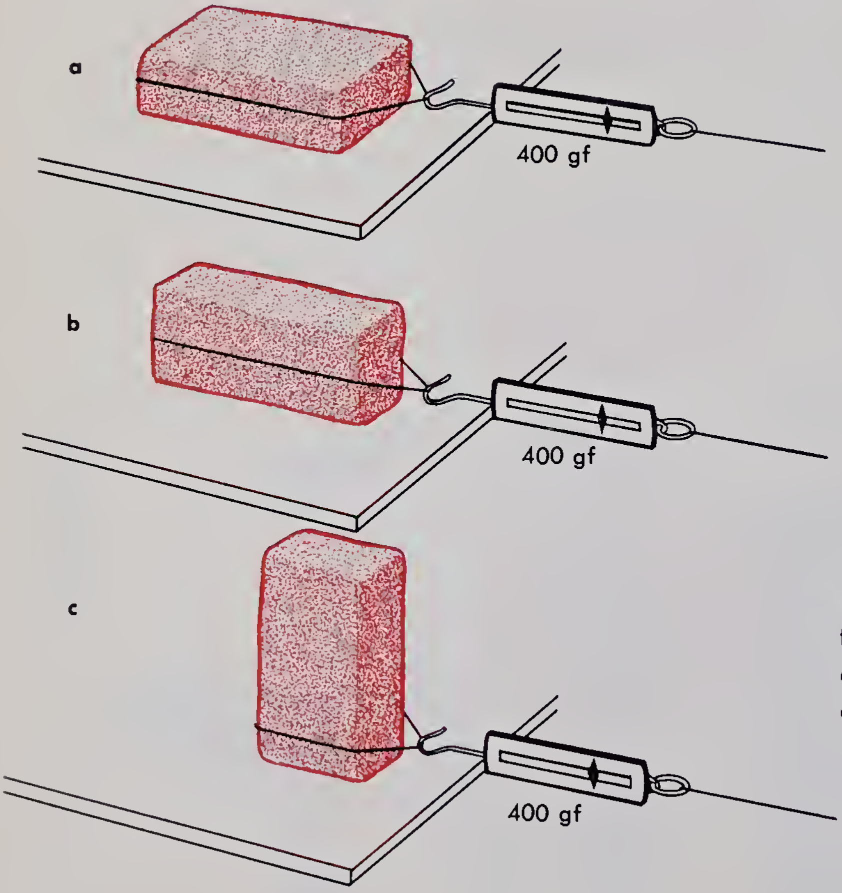


Figure 7–6 This experiment indicates that the force of friction is independent of the area in sliding contact, other things being equal.

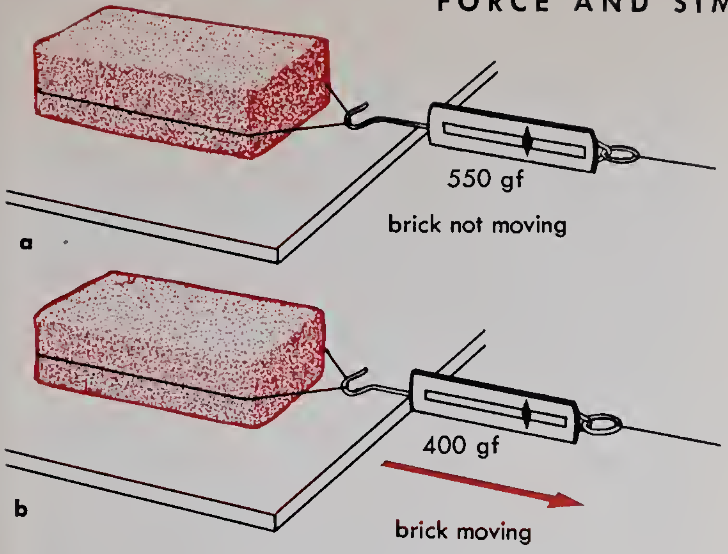


Figure 7–7 This experiment indicates that starting friction is greater than sliding friction.

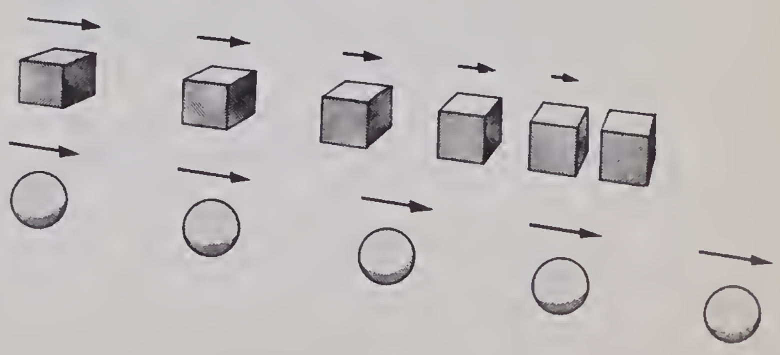
sion in the spring (Fig. 7–7) is observed just before the brick is set into motion and again while it is moving with uniform velocity, the observations show that *starting friction is greater than sliding friction.* The reason is that when the brick has been sitting on the floor without moving, it has settled slightly. This brings the surfaces closer together, increasing their attraction for each other, and also causing the irregularities to become more closely interlocked. The increased force at the start is also partly due to the $F = ma$ force needed to accelerate the brick.

Suppose you give an object a push so that it starts to slide. If you stop pushing, the object may keep on sliding for a while, but it slows down and eventually stops, due to the unbalanced force of friction. One way to compare the force of friction in two situations is to see which of two objects slows down faster. Figure 7–8 illustrates a comparison between the frictional force acting on a block of wood and the frictional force acting on a wooden ball of the same weight. The block of wood slows down much more quickly, showing that *sliding friction is greater than rolling friction.*

If you try pulling a brick at one speed, and then at a slightly greater steady speed, you will probably find that the force is just about the same in both cases. This observation led scientists to believe that the force of friction was not influenced by speed, except for the difference between starting and sliding friction. However, accurate measurements in the past twenty years have shown that friction decreases slightly when the speed goes up (except when the speed is extremely low). Since friction is largely due to the attraction between surfaces, the attraction is greater when the motion is slow because there is more time for the surfaces to settle closely together. Slow speeds encourage the stick-slip type of movement. The attraction of the slowly moving surfaces causes them to stick. Then the forward force jerks them along for an instant, until they happen to be close enough together again to stick. If they are moving rapidly past each other, there is less time to settle into a good sticking position. Thus a door may creak (making the stick-slip noise) when you open it slowly, but may not creak when you open it quickly.

When the two surfaces move extremely slowly (about 10^{-6} cm/sec in the case of steel, and about 10 cm/sec in the case of lead), the frictional force becomes less again, probably because at these speeds the molecules of the metal actually flow over one another to a slight extent; that is, they begin to behave somewhat like liquids near their surfaces.

Figure 7–8 The wooden ball and the wooden block were moving with the same speed at the start. The block soon came to rest, while the ball kept on rolling. The unbalanced force that slowed both was friction. This experiment shows that sliding friction is greater than rolling friction.



The laws of friction here may be different from those you find in other books. This is partly because scientists have but an incomplete understanding of friction. The laws of friction have always been laws of the "approximately true" kind. You will find if you do some experiments shown in the illustrations, that it is very difficult to get answers that agree all the time. This is because pulling the brick along a board or table changes the surface. You may smooth out the board, or you may roughen it during the experiment. Two boards or tables that look alike may give different values. The study of the effect of speed is difficult to perform. Because of these facts the laws of friction are not at all precise. They are **empirical laws**; laws that agree more or less with experimental observations, but do not have a sound basis in theory. Contrast them with the law of gravitation, which is so precise that it has been used to predict the positions of planets hundreds of years in the future and to determine the launching angles and speeds of ballistic missiles and satellites that must follow almost perfect paths.

7–4 It is often necessary to control friction. Controlling friction may mean decreasing it, as in moving parts in an automobile, or increasing it, as in the brakes and tires of the same automobile. The two factors that can be controlled most readily are the nature of the surfaces and the kind of motion. A few examples illustrate this.

Brake linings are made of material which is selected for its high amount of friction and resistance to wear. In addition, they are kept dry to increase the friction. Lugs, or traction bars, on tractor tires are designed to increase friction and to resist wear. The tread of an automobile tire is also designed to increase friction.

A very common way to reduce friction is to substitute rolling for sliding friction. Roller bearings and ball bearings are used in the axles of wheels on automobiles, bicycles, and roller skates. They serve to provide rolling friction between the stationary axle and the rotating wheel. These bearings are usually enclosed in a bearing race that serves to keep the individual ball or roller bearings in their proper position.

Another way to reduce friction is through lubrication. Usually this takes the form of oil, grease, or graphite placed between sliding or rolling surfaces. Oil forms a thin film between the moving surfaces. Although this film is very thin, sometimes only a few molecules thick, it almost completely prevents one surface from touching the other, thus changing the nature of the sliding surfaces and reducing friction and wear. Graphite provides lubrication in a somewhat different way. Graphite consists of flat smooth crystals, which easily slide over each other.

If you want to do an experiment that is almost friction free, get a slab of dry ice and slide it across a table. Dry ice is solid carbon dioxide. At room temperature and pressure, carbon dioxide evaporates without turning to a liquid first. Therefore at the bottom of your piece of dry ice, a constant supply of carbon dioxide gas is being formed. The slab floats on a tiny film of gas, which acts as a very superior lubricant between the slab and the table. Small slabs of dry ice can be used under heavy weights to make them almost frictionless for experiments to test the laws of motion.

7–5 Work must be done to overcome friction. The force required to overcome the force of friction is exerted through a distance. This means that work is done and energy is required. What happens to this mechanical energy? Almost all of it is converted into heat energy. When you rub your hands briskly together, you can feel the heat generated by friction. Scratching a match or starting a fire by striking flint on steel or rubbing sticks together are also examples of mechanical energy being converted to heat energy through friction. The bearings of a machine get hot because of the conversion of frictional energy to heat. This is the chief cause of inefficiency in machines, and engineers are continuously trying to design machines having a minimum of friction.

A small amount of frictional energy may be converted into the energy of sound (as in the case of the creaking door) or even into light energy if the bodies get hot enough (as when you strike flint against steel).

Self Check

1. In which of the following situations is friction a help and in which is it a disadvantage? (a) walking; (b) inside the motor of an automobile; (c) in the brakes of an automobile; (d) in the bearings of a bicycle.
2. What causes the squeak of a door hinge?
3. What is the major cause of friction?
4. What is another cause of friction?
5. What is always true about the direction of the force of friction?
6. Name three factors that influence the magnitude of the force of friction.
7. The force of friction between a 100-lb box and the floor is 20 lb. What is the friction if a 100-lb boy sits on the box?
8. As the speed of a moving object increases, what generally happens to the force of friction?
9. Describe two common ways to reduce friction.
10. What becomes of the energy used when work is done against friction?

Discussion Questions

1. What would be some of the results if the force of friction suddenly ceased to exist?
2. A force of 10 lb will keep a box moving across a horizontal floor at uniform velocity. Therefore the force of friction is 10 lb. Now suppose that the box is at rest and you push it with a force of 8 lb. What is the force of friction in this case?
3. Can you give any reasons why the force of friction should not depend on the overall area of the surfaces? Use Fig. 7–6 in your discussion.

The Coefficient of Friction

7–6 The force of sliding friction is proportional to the normal force. In the experiment of Fig. 7–4 you saw that when the perpendicular force (called the **normal force**) pressing two sliding surfaces together is doubled, frictional force is doubled; when the normal force is tripled, frictional force is likewise tripled; and so on. That is, the frictional force, F_f, between two sliding surfaces is directly proportional to the normal force, F_n, between them. This can be expressed in the simpler and briefer language of mathematics thus:

$$F_f = kF_n$$

where k is a constant. This constant is called the coefficient of friction. A formula for it can be derived from the one above:

$$k = \frac{F_f}{F_n}$$

The **coefficient of friction** can be defined as the ratio between the frictional force and the normal force. Coefficients of friction vary greatly and depend on the surfaces involved. As was pointed out earlier, they also change because the surfaces are changed by the rubbing. Some typical values for coefficients of friction are shown in Table 7–1 below. Remember that these are approximate values only.

The experiment of Fig. 7–5a can be used to find the coefficient of friction of the materials involved. If the brick weighs 1000 gf, then this is the normal force, since the floor is horizontal. The force required to move the brick with uniform velocity is 400 gf. Therefore:

$$k = \frac{400 \text{ gf}}{1000 \text{ gf}}$$

$$k = 0.40$$

Notice that the coefficient of friction has no units since it is the ratio of two forces.

7–7 The coefficient of friction is used to solve problems. Many practical problems can be solved using the coefficient of friction. Example 1 at the right shows how to use the values listed in Table 7–1.

Table 7–1 APPROXIMATE VALUES OF COEFFICIENT OF FRICTION

Surface	*Coefficient*
Wood on wood, dry	0.25–0.50
Metal on oak, dry	0.50–0.60
Metal on oak, wet	0.24–0.26
Stone on wood	0.40
Metal on metal, dry	0.15–0.20
Smooth metal on smooth metal, greased	0.05

EXAMPLE 1

A 200-lb block of stone rests on a wooden floor. What horizontal force is required to move it? How much work is done in dragging it a distance of 15 ft?

Given: $F_n = 200$ lb
$s = 15$ ft

To find: F_f and Work

Solution: $F_f = kF_n$
$= 0.40 \times 200$ lb
(k is found from Table 7–1)
$= 80$ lb

Since this is the backward force of friction, a forward force equal to this is needed to keep the block moving with uniform velocity. Therefore:

Work $= Fs$
$= 80 \text{ lb} \times 15 \text{ ft}$
$= 1.2 \times 10^3$ ft · lb, Answer

Self Check

1. If a 30-lb box is dragged across a horizontal floor by a force of 10 lb, what is the normal force? What is the coefficient of friction?
2. How much work is done to drag a 50-kg wooden box 5.0 m across a floor if the coefficient of friction is 0.30?

Problems

A ✓**1.** A boy is able to exert a horizontal force of 200 N. How many kilograms of stone can he drag along a surface with a coefficient of friction of 0.25?

✓**2.** The same boy attempts to drag a 200-kg load a horizontal distance of 40 m. What must be the coefficient of friction if he is to be successful, and how much work will he do?

✓ **3.** A man pushes a 100-kg block a distance of 5.0 m across a surface having a coefficient of friction of 0.20. It takes him 8.0 sec to do the job. Find his power output.

✓ **4.** A boy pulls a 5.0-kg sled at uniform velocity across a horizontal patch of snow. The sled rope makes an angle of 30° with the horizontal. If he pulls with a force of 10 N, what is the coefficient of friction? (Hint: The normal force is not what you might think at first.)

5. If the coefficient of friction between a block and a board is 0.40, what force is required to push the 100-lb block up a 20° slope?

B

6. A block of wood is placed on one end of a board. Then the end of the board is raised until, when the block is given a slight push, it slides down the board with uniform velocity. Prove that $k = \tan A$, where A is the angle the board makes with the horizontal.

An Inclined Plane Is a Simple Machine

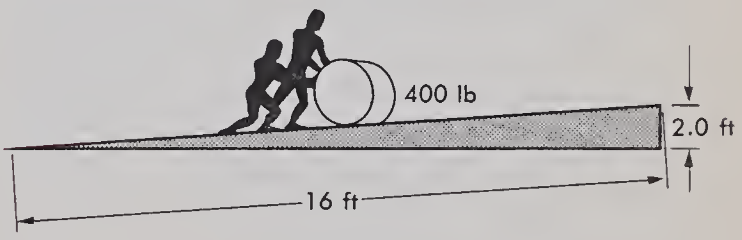
7–8 What is a machine? Eggbeaters, automobile jacks, a block and tackle, a loading ramp — all of these are machines. Just what do they have in common? In other words, what is a machine? A **machine** is a mechanical device that makes it possible to do work more conveniently by increasing the speed of an operation, or decreasing the force that must be supplied, or by changing the direction of force. It is easier to beat an egg with an eggbeater than with a fork because you can make the blades go faster than the fork. It would be impossible for most people to lift the rear axle of a car so a tire could be changed. With a jack, even a child can raise the load.

A machine is not a source of energy. To get it to do work, you must supply it with energy — you turn an eggbeater handle or push down on a jack handle. The mechanical work done on a machine is called the **work input**; and the mechanical work accomplished by the machine on some other object is called its **work output**. With the car jack, for example, the work input for each push you make is equal to the force you exert multiplied by the distance your hand moves. The work output is the weight raised, multiplied by the distance it is raised.

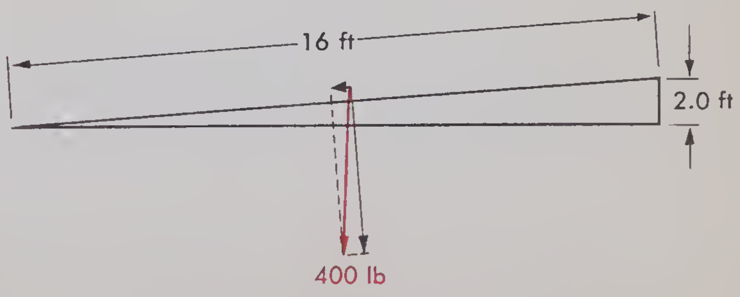
There are many kinds of machines. But in physics, as in any science, matters have been simplified by grouping similar devices together. When this is done, many of the simpler machines can be classified into two groups: inclined planes and levers.

7–9 Energy is conserved when work is done. The two men in Fig. 7–9a are rolling a 400-lb drum of syrup up a 16-ft plank onto a loading platform 2.0-ft high. How much work have they done when they get to the top? They have succeeded in raising the drum a height of 2.0 ft, giving it poten-

Figure 7–9 a. The two men rolling the syrup drum up the inclined plane exert a force parallel to the plane which is less than the weight of the drum.



b. The force that must be used to roll the barrel up the incline is equal in magnitude to the component of the weight parallel to the slope.



tial energy. The work output is equal to the potential energy of the drum:

$$\begin{aligned}\text{work output} &= E_p = Wh \\ &= 400\ \text{lb} \times 2.0\ \text{ft} \\ &= 8.0 \times 10^2\ \text{ft}\cdot\text{lb}\end{aligned}$$

Is this the same as the work input, the work actually done by the men? Energy can neither be created nor destroyed. If there were no friction, then the work input would have to be equal to the work output. But if there is friction, some of the work done by the men will be converted to heat energy along the board, and they will have to do more than 800 ft · lb of work to raise the syrup barrel.

The law of conservation of energy, as applied to a simple machine, is called the **law of work**. It is:

work input = work output (if no work is wasted)
work input = work output + work wasted

Work is always wasted in overcoming friction. It may also be wasted if part of the apparatus that carries the load has to be lifted. For example, a giant scoop shovel may weigh many hundreds of pounds, yet the work done in lifting it is wasted.

7–10 Machines provide a mechanical advantage. You know from past experience that it would be easier to roll the barrel up the plank than to lift it. In Chapter 6 you learned how to calculate the force that the men must use (see Fig. 7–9b). The component of the weight parallel to the slope is F. Since the force triangle is similar to the triangle of the slopes:

$$\frac{F}{400\ \text{lb}} = \frac{2.0\ \text{ft}}{16\ \text{ft}}$$

$$F = \frac{2.0\ \text{ft} \times 400\ \text{lb}}{16\ \text{ft}}$$

$$= 50\ \text{lb}$$

A force of 50 lb up the slope will just balance the 50-lb component down the slope, and will therefore keep the barrel moving at uniform velocity if there is no friction. Since the barrel is being rolled, the friction is probably quite small.

You can also use the law of work to find the force. Assume that the friction is zero and use the form:

work input = work output

The work input in this task was done by rolling the drum a distance of 16 ft. Since work $= Fs$:

$$F \times 16\ \text{ft} = 400\ \text{lb} \times 2.0\ \text{ft}$$

$$F = \frac{800\ \text{ft}\cdot\text{lb}}{16\ \text{ft}} = 50\ \text{lb}$$

Both methods give the same answer. Use the method you prefer, or use both to check your accuracy.

The inclined plane was a great help to the workmen. Without it they might have found it impossible to raise the drum. The inclined plane itself did no work, but it made it possible for the men, by exerting a small force (50 lb), called the **input force** (F_i), to raise a large weight (400 lb), called the **output force** (F_o). The ratio of output force to input force in a machine is called the **mechanical advantage** (**MA**) of the machine:

$$\text{mechanical advantage} = \frac{\text{output force}}{\text{input force}}$$

$$\text{MA} = \frac{F_o}{F_i}$$

In this case:

$$\text{MA} = \frac{400\ \text{lb}}{50\ \text{lb}} = 8.0$$

Notice that the units cancel out when you calculate mechanical advantage. The mechanical advantage is always a pure number — without units.

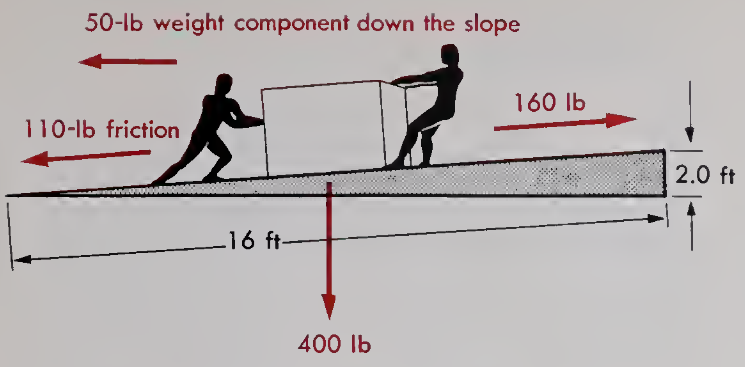


Figure 7–10 If a load is *slid* instead of *rolled* up an inclined plane, friction may be greatly increased.

7–11 The ideal mechanical advantage is never attained. So far friction has been slight, and it has been ignored in order to make the analysis simpler. But in actual situations there is always some friction. For example, suppose that instead of the 400-lb syrup drum, the workmen drag a 400-lb crate up the inclined plane and that the force of friction is 110 lb (Fig. 7–10). What input force will the men have to exert?

50 lb would be needed if there were no friction (as in the drum problem).
110 lb must be supplied to overcome friction.
160 lb is the total input force required.

The output force is still 400 lb. The mechanical advantage has changed:

$$\text{MA} = \frac{F_o}{F_i} = \frac{400 \text{ lb}}{160 \text{ lb}} = 2.5$$

The mechanical advantage that takes into account the real frictional force is called the **actual mechanical advantage**; the mechanical advantage that would exist if the friction were zero is called the **ideal mechanical advantage.**

The ideal mechanical advantage can be calculated from the geometry of the inclined plane. Let the distance the men exert their input force along the slope be called the **input distance** (s_i) and let the height the load is raised be called the **output distance** (s_o). If there were no friction, the law of work would be:

$$\text{work input} = \text{work output}$$

$$F_i s_i = F_o s_o$$

This can be rearranged:

$$\frac{s_i}{s_o} = \frac{F_o}{F_i}$$

Since F_o/F_i is the definition of mechanical advantage, then s_i/s_o must be the mechanical advantage when there is no friction. It is the ideal mechanical advantage of an inclined plane. The inclined plane of Fig. 7–9 and 7–10 has an ideal mechanical advantage of $\frac{16 \text{ ft}}{2.0 \text{ ft}} = 8.0$.

The definitions of actual and ideal mechanical advantage given for the inclined plane also hold for other machines. For the inclined plane only, the ideal mechanical advantage can also be defined as:

$$\text{ideal MA} = \frac{\text{distance along the slope}}{\text{height of the plane}}$$

7–12 No machine is perfectly efficient. Friction or no friction, you can neither create nor destroy energy. Analyze the work input and work output in the problem of Fig. 7–10:

Work input: To raise load
50 lb × 16 ft = 800 ft · lb
To overcome friction
110 lb × 16 ft = 1760 ft · lb
Total 2560 ft · lb

Work output:
Stored as potential energy of raised load 400 lb × 2.0 ft = 800 ft · lb
Converted to heat energy by friction 1760 ft · lb
Total 2560 ft · lb

Of the work output, only the potential energy of the raised load is useful. Thus you see that although the use of this simple machine has not *destroyed* energy, it has *wasted* it; that is, the machine has not been perfectly efficient.

Efficiency is defined as $\dfrac{\text{useful work output}}{\text{total work input}}$.

In the case of the crate and the inclined plane:

$$\text{efficiency} = \frac{800 \text{ ft·lb}}{2560 \text{ ft·lb}} = 0.31 = 31\%$$

Note the efficiency is a number without units. It is usually expressed as a percent rather than as a fraction.

The efficiency of a simple machine can also be calculated from the formula:

$$\text{efficiency} = \frac{\text{actual MA}}{\text{ideal MA}}$$

You should be able to prove that this formula is correct. Study Example 2 at the right and note how the problem is checked.

EXAMPLE 2

A box weighing 50.0 kgf is pushed up a slope 10.0 m long and 1.0 m high. If it takes a force of 8.0 kgf to push the box, find (a) the efficiency of the incline and (b) the force of friction.

Given: $F_o = 50.0$ kgf $\quad s_o = 1.0$ m

$F_i = 8.0$ kgf $\quad s_i = 10.0$ m

To find: (a) efficiency; (b) force of friction

Solution: (a)

$$\begin{aligned} \text{work input} &= F_i s_i \\ &= 8.0 \text{ kgf} \times 10.0 \text{ m} \\ &= 80 \text{ kgf} \cdot \text{m} \end{aligned}$$

$$\begin{aligned} \text{Useful work output} &= F_o s_o \\ &= 50.0 \text{ kgf} \times 1.0 \text{ m} \\ &= 50 \text{ kgf} \cdot \text{m} \end{aligned}$$

$$\begin{aligned} \text{efficiency} &= \frac{\text{useful work output}}{\text{total work input}} \\ &= \frac{50 \text{ kgf} \cdot \text{m}}{80 \text{ kgf} \cdot \text{m}} = 0.62 \\ &= 62\%, \text{ Answer} \end{aligned}$$

Check by using another method:

$$\text{actual MA} = \frac{F_o}{F_i} = \frac{50.0 \text{ kgf}}{8.0 \text{ kgf}} = 6.2$$

$$\text{ideal MA} = \frac{s_i}{s_o} = \frac{10.0 \text{ m}}{1.0 \text{ m}} = 10$$

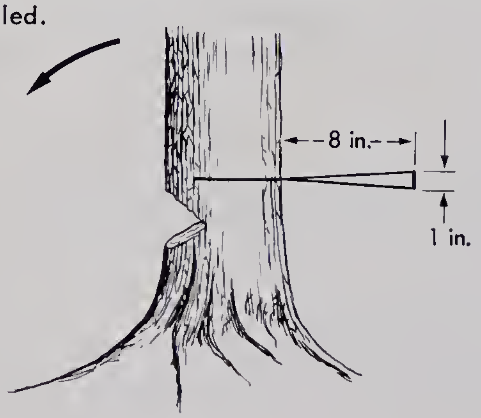
$$\begin{aligned} \text{efficiency} &= \frac{\text{actual MA}}{\text{ideal MA}} = \frac{6.2}{10} \\ &= 62\%, \text{ Check} \end{aligned}$$

(b) work done against friction

$$\begin{aligned} &= \text{total input} - \text{useful output} \\ F_f \times 10.0 \text{ m} &= 80 \text{ kgf} \cdot \text{m} - 50 \text{ kgf} \cdot \text{m} \\ &= 30 \text{ kgf} \cdot \text{m} \\ F_f &= 3.0 \text{ kgf, Answer} \end{aligned}$$

7–13 A wedge is an inclined plane. The tree trunk in Fig. 7–11 has been notched with an axe at the left and sawed nearly through on the right. The lumberjack inserts the point of a steel wedge in

Figure 7–11 When a wedge is driven toward the left, the right side of the tree is tilted and the tree topples toward the left, as shown by the arrow. The notch cut low on the left helps determine the direction in which the tree will be felled.



the cut made by the saw and pounds on it. The wedge is shaped like an inclined plane, but instead of being a stationary one, it moves, exerting the input force. The output force is provided by the weight of the tree. If the wedge is 8 in long and 1 in thick at the outer end, then when the wedge has moved 8 in, the outer edge of the tree will have been raised 1 in. The ideal MA is 8 in/1 in or 8, but since there is a great deal of friction, the actual MA will be much smaller. This means, of course, that the efficiency of a wedge is low.

You may never have used a wedge to fell lumber or to split logs, but you have surely used one many times. Knives, hatchets, chisels, and planes are all wedges. A pair of scissors is really two wedges whose sharp edges slide past each other. Wedges are often used to keep doors from closing. In this case, too, they are simple machines. A push or a kick on the wedge produces a large frictional force, one large enough to keep the door from moving.

7–14 A screw is an inclined plane. A screw is a type of inclined plane wrapped around a cylinder, as shown in Fig. 7–12a. The jackscrew shown in Fig. 7–12b involves a screw and also a lever.

Using screws and wedges usually produces much friction. In both cases, of course, the friction is really an advantage. It prevents the output force from squeezing the wedge out or turning the screw backwards when the input force is removed.

Many kinds of screws are used in common devices around the house: nuts and bolts, wood screws, adjustable piano stools, the feeding mechanism of a food grinder, the threaded tip of a bit. Propellers on ships and airplanes are screws that dig their way through the water or air.

Self Check

1. What is a machine?
2. What two kinds of machines include many simple machines?
3. State the law of work in the case in which there is friction.
4. A 60-lb cylinder is rolled up an inclined plane 5.0 ft long and 1.0 ft higher at one end than the other. Assume that there is no friction. (a) What is the work output? (b) What is the work input? (c) What is the mechanical advantage? (d) What is the input force?
5. If a force of 20 N is applied to a jackscrew, it can lift a load of 3000 N. What is the mechanical advantage?

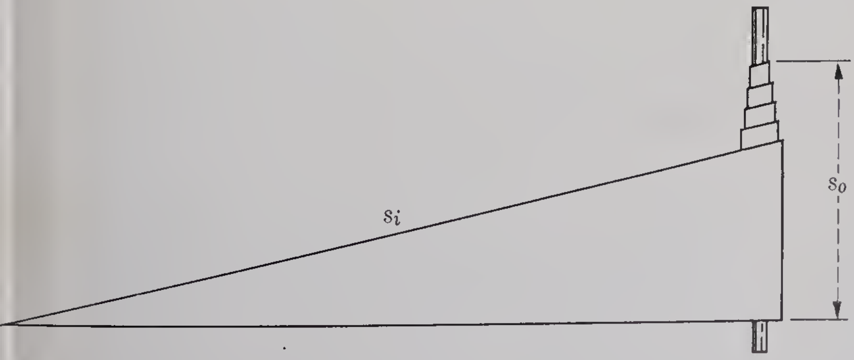


Figure 7–12a A screw may be thought of as an inclined plane wrapped around a cylinder. For the entire screw, the s_o would be the height of the inclined plane, while s_i would be its slant length.

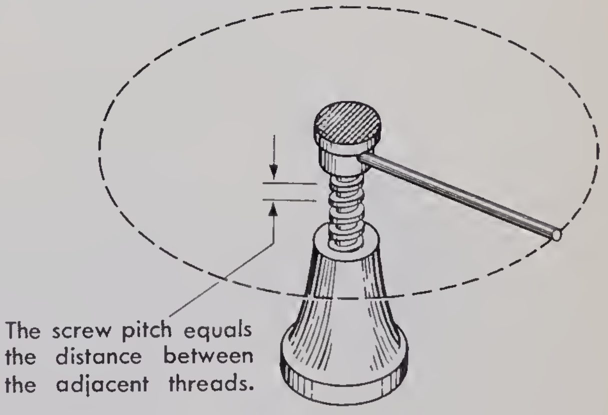

The screw pitch equals the distance between the adjacent threads.

Figure 7–12b In this construction jack the shaft rises by a distance equal to the pitch of the screw every time the jack handle is pushed through a complete circle. Therefore, s_o is the pitch and s_i is $2\pi l$, where l is the length of the jack handle.

6. Is the answer you gave to Problem 5 the actual or the ideal MA?
7. Compare the size of the actual MA with that of the ideal MA in any machine.
8. What is the work input to a machine that does 5000 J of work at an efficiency of 50%?
9. Why is a screw considered to be a form of inclined plane?
10. What other machine was described in this section as being a form of inclined plane?

Problems

Assume that there is no friction in Problems 1 and 2.

A 1. A loading ramp for putting crates of apples in a truck consists of a set of steel rollers arranged like rungs in a ladder. Calculate the work input, work output, and the mechanical advantage if 600 lb of apples are sent up a ramp 12 ft long and 3.0 ft higher at the truck end than at the other end.

2. The mechanical advantage of an inclined plane is 4. What is the work input when a 2000-N load is moved 10 m along the slope?

3. An inclined plane is 6.0 m long and 1.5 m higher at one end than the other. A force of 80 N is required to push a box that weighs 250 N up the slope. Find the actual and ideal mechanical advantage.

4. An inclined plane is 20.0 m long and 4.0 m high. A man rolls a 60-kg barrel up the slope, using a force of 20 kgf. Find the efficiency and the force of friction.

5. Show how this equation is derived: efficiency = actual MA/ideal MA.

6. With what force would you have to hammer on a wedge 20 in long and 0.5 in thick at the broad end in order to lift a 4000-lb load if there were no friction?

7. With what force would you have to hammer on the wedge of Problem 6 if the wedge had an efficiency of 50%?

8. What is the efficiency of a jackscrew if the pitch of the screw is ¼ in, the distance from the end of the handle to the center is 2 ft, and a force of 100 lb is required at the end of the handle to raise a load of 6 tons?

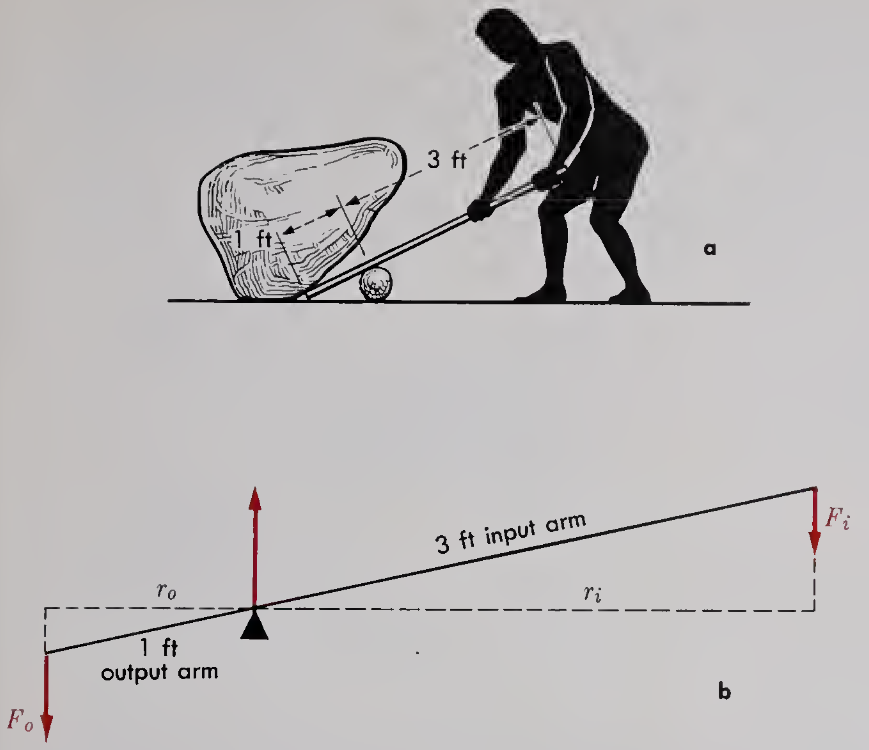
B 9. Find the coefficient of friction along an inclined plane 20 m long and 6.0 m high if an input force of 50 kgf parallel to the plane will move a load of 100 kg up the slope.

Discussion Questions

1. Over the centuries many people have hoped to make a "perpetual motion machine"— one that, once started, would continue to do work indefinitely without being supplied with energy. What fundamental law is violated by such a machine?
2. If friction were eliminated completely from the bearings of a wheel, and if it were in a vacuum so that there was no air resistance to slow it, it should go forever when once started. Would this be a perpetual motion machine in the sense of the definition of Question 1?

A Lever Is a Simple Machine

7–15 The law of moments applies to a lever. The man in Fig. 7–13a is using a wrecking bar to raise a heavy rock. A rigid bar that can be rotated about a fulcrum in order to lift a load is a simple machine, called a **lever.** In this case the fulcrum is at the point where the bar rests on the stone. The man exerts an input force at one end of the bar, and the stone exerts the output force at the other end. The forces



a. A wrecking bar is a simple machine of the lever type.

b. The forces acting on the bar above are shown in the diagram at the left. For equilibrium, the moments around the fulcrum must balance:

$$F_o \times r_o = F_i \times r_i$$

Dividing through by $F_i \times r_o$, you get:

$$\frac{F_o}{F_i} = \frac{r_i}{r_o}$$

Since the triangles are similar:

$$\frac{r_i}{r_o} = \frac{\text{input arm}}{\text{output arm}}$$

Therefore:

$$\text{MA} = \frac{\text{input arm}}{\text{output arm}}$$

Figure 7–13

acting on the bar are diagramed in Fig. 7–13b. The distance along the bar from the fulcrum to the input force is called the **input arm**; that from the fulcrum to the output force is the **output arm**. When the law of moments is applied to the lever, the explanation under Fig. 7–13b shows that:

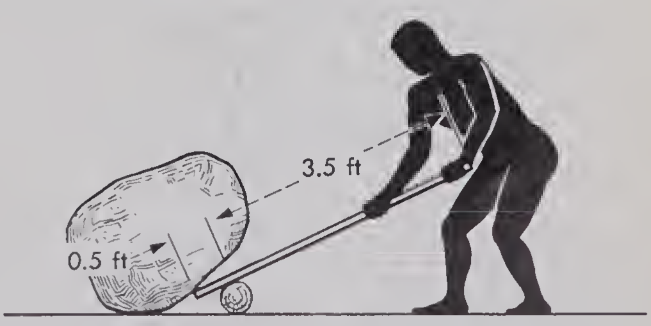
$$\text{MA} = \frac{\text{input arm}}{\text{output arm}}$$

Since friction is of minor importance with a lever, this equation usually serves both for actual and ideal MA. However, the weight of the bar itself may have an effect. Since the center of gravity of the bar is to the right of the fulcrum in Fig. 7–13, the weight would actually help to lift the rock, so the man would not have to exert as large an effort force as otherwise. However, in physics you never get something for nothing. Although the weight of the bar helps the man to do his work, he had to lift the bar in the first place. The extra work he gets out of the bar on the push down is equal to the work he did to raise it.

The mechanical advantage of a lever can be varied by a change in the position of the fulcrum, as shown in Fig. 7–14.

Figure 7–14 If the fulcrum is moved, the mechanical advantage of the wrecking bar changes. Here the ideal MA is

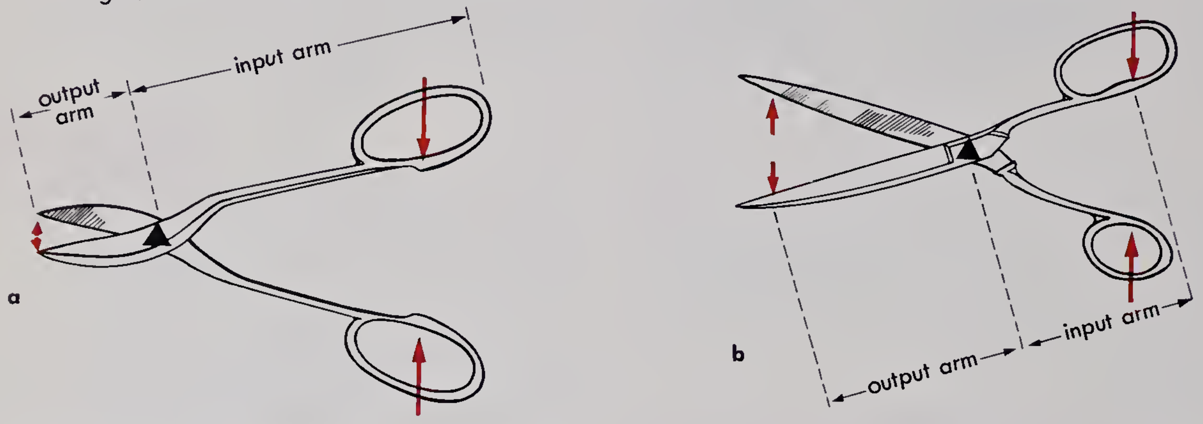
$$\frac{3.5\text{ ft}}{0.5\text{ ft}} = 7.$$



7–16 Levers are very common. Figure 7–15 shows a variety of levers in common use. Notice that some have the fulcrum at the end and some nearer the center. Notice for the wheelbarrow and nutcracker, for example, how the output and input arms are measured when the fulcrum is at the end. A machine is considered to be a lever even if the bar is bent.

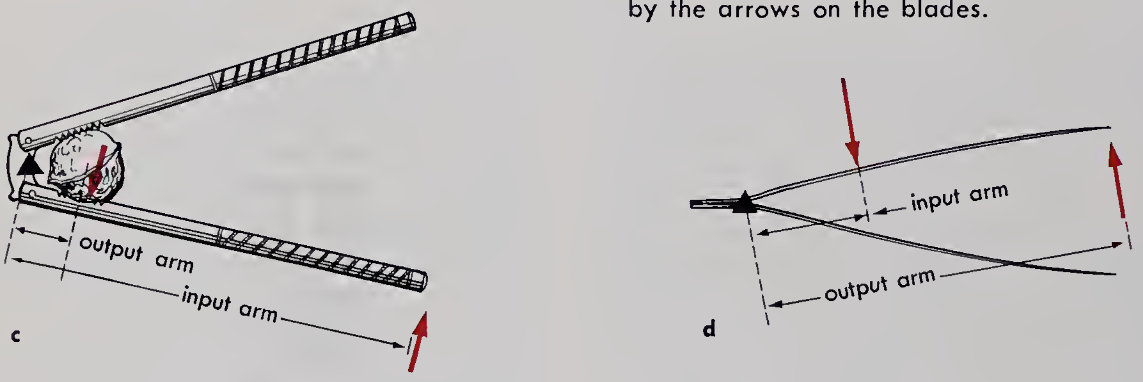
Some machines are designed to multiply the speed or distance of an operation instead of the force. Shears with blades

Figure 7–15 All these devices are levers. The fulcrum in each case is indicated by a triangle.



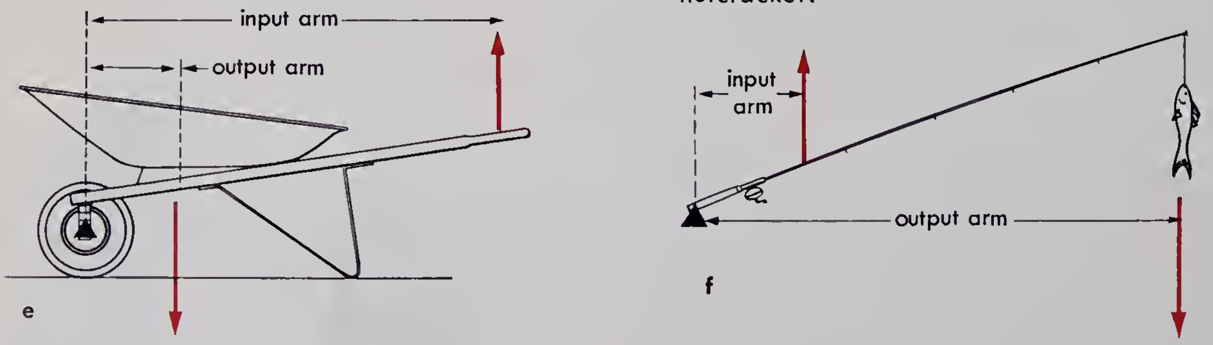
a. Tinsnips and pliers are made of a pair of levers. The force that does the cutting is greater than the force on the handles.

b. The MA of these shears is greater than 1 when the cutting starts, and becomes less than 1 when cutting occurs at the place indicated by the arrows on the blades.



c. A nutcracker is a pair of levers with the fulcrum at one end. Notice how the input and output arms are measured in this case.

d. Tweezers also have the fulcrum at one end, but the positions of the input and output forces are reversed, as compared with the nutcracker.



e. A wheelbarrow has an input arm much longer than its output arm and thus has a large MA.

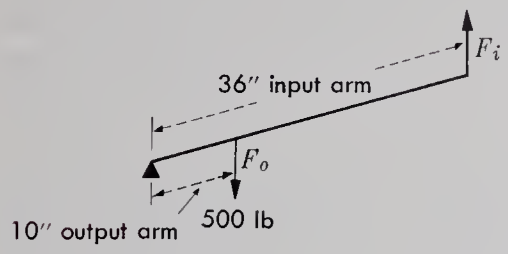
f. A fishpole has a mechanical advantage that is less than 1. This makes possible greater speed of movement at the output end.

EXAMPLE 3

A man carries a 500-lb load of rocks in a wheelbarrow. The center of gravity of the load is 10 in. from the axle of the wheel; he holds the handles at a point 3.0 ft from the axle. Find (a) the ideal MA of the wheelbarrow; (b) the input force. (Ignore the weight of the wheelbarrow.)

Given:

To find: (a) ideal MA; (b) F_i



Solution: (a)
$$\text{ideal MA} = \frac{\text{input arm}}{\text{output arm}} = \frac{36\ \text{in}}{10\ \text{in}} = 3.6,\ \text{Answer}$$

(b) assume ideal MA = actual MA

$$\text{actual MA} = \frac{F_o}{F_i}$$

$$3.6 = \frac{500\ \text{lb}}{F_i}$$

$$3.6F_i = 500\ \text{lb}$$

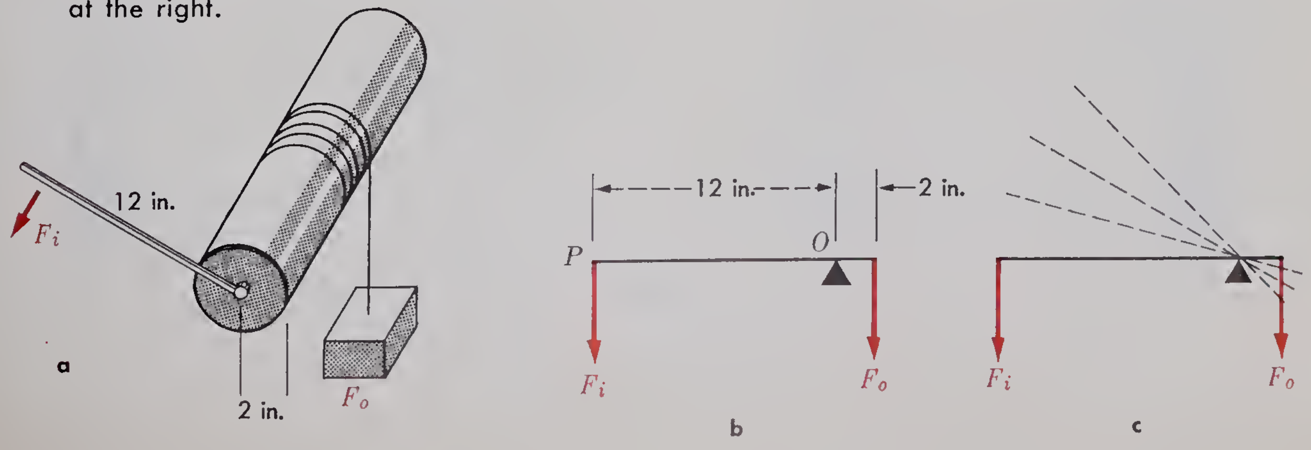
$$F_i = 1.4 \times 10^2\ \text{lb},\ \text{Answer}$$

longer than the handles, and a fishpole are examples (Fig. 7–15b and f). They have a mechanical advantage that is less than 1. With a fishpole you might exert a force of 10 lb near the handle in order to lift a 1-lb fish. With a heavier fish you slip your hand along the pole to increase the MA. The chief values of this machine are the speed with which you are able to cast and to maneuver the fish and the distance you can cover. A bicycle is another machine in which increase in speed is desired. Study Example 3 above. In actual practice can the weight of the wheelbarrow be ignored?

7–17 A wheel and axle is a lever.

The simplest form of wheel and axle is sketched in Fig. 7–16a. In Fig. 7–16b you see it from the end. The length of the handle (PO) is the input arm, and the radius of the cylinder (OQ) is the output arm. The law of moments applies here, just as for the wrecking bar, and the line POQ may be thought of as a lever. The lever keeps rotating, as shown in Fig. 7–16c. For the wheel and axle shown, the ideal MA is $\frac{12\ \text{in}}{2\ \text{in}}$, or 6. There is always friction with a wheel and axle, so the actual MA is less than this.

Figure 7–16 The simple wheel and axle at the left can be thought of as a lever. The center diagram shows the situation as seen from the end. The lever rotates continuously as shown at the right.



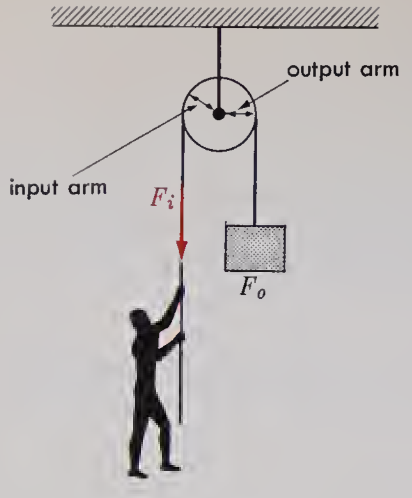


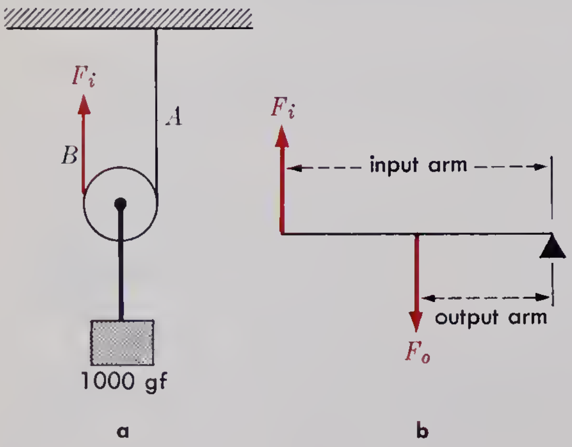
Figure 7–17 A single fixed pulley is like a continuously rotating lever with a mechanical advantage of 1.

7–18 A pulley is a lever. A single fixed pulley, as in Fig. 7–17, is a lever with the fulcrum at the center. The mechanical advantage of a single fixed pulley is 1. Its only use is that it changes the direction in which the force must be exerted.

In Fig. 7–18a, a single pulley is rigged as a movable pulley. The diagram in Fig. 7–18b shows that this may be thought of as a lever with the fulcrum at one end. The input arm is equal to the diameter of the pulley wheel, and the output arm is equal to its radius. Therefore:

$$\text{ideal MA} = \frac{\text{input arm}}{\text{output arm}} = \frac{\text{diameter}}{\text{radius}} = 2$$

Figure 7–18 A single movable pulley may be thought of as a lever with a mechanical advantage of 2.



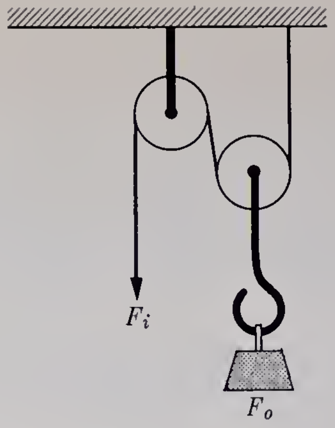


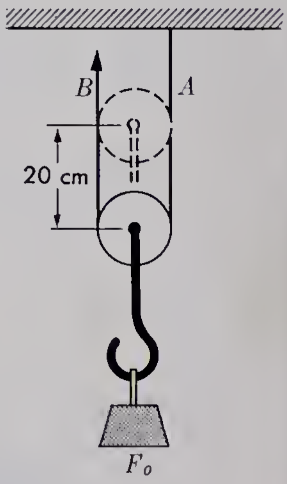
Figure 7–19 In this pulley combination, a single fixed pulley has been added to the single movable pulley device. The second pulley merely changes the direction of the input force. It does not alter the MA of the system.

In Fig. 7–19 a single fixed pulley has been added to the single movable pulley, the purpose being to permit the operator to exert the input force downward rather than upward. The addition of this fixed pulley does not affect the MA of the system.

There are two other ways to analyze the pulley system of Fig. 7–18. For example, the load of 1000 gf is obviously supported by the two strands of rope, A and B. Since these two strands share the load equally, each has a tension of 500 gf when there is no friction. But the tension in B is also the input force, F_i. Therefore the ideal MA is:

$$\text{ideal MA} = \frac{F_o}{F_i} = \frac{1000 \text{ gf}}{500 \text{ gf}} = 2.00$$

Figure 7–20 When the movable pulley rises 20 cm, a total of 40 cm must be taken in at B. This is another way of analyzing the MA of a single movable pulley system.



Another analysis is illustrated in Fig. 7–20. Here the pulley system is shown in two positions. The dotted diagram shows the movable pulley 20 cm higher than the solid line diagram; that is, $s_o = 20$ cm. To accomplish this, each of the two supporting strands is shortened 20 cm. Therefore B must have moved up 40 cm and $s_i = 40$ cm. Consequently:

$$\text{ideal MA} = \frac{s_i}{s_o} = \frac{40\text{ cm}}{20\text{ cm}} = 2.0$$

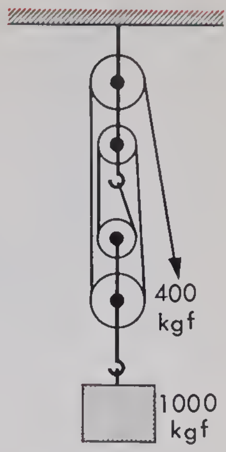
Of these three methods for determining the ideal MA of a pulley system the simplest one is to count the strands. A useful rule is that the ideal MA of a pulley system like the ones shown here is equal to the number of strands directly supporting the moving pulley or pulleys. Note that if the last strand from a fixed pulley is downward, it merely changes the direction of the effort force; do not count that strand.

The combination of a set of fixed pulleys with a set of movable ones, arranged like those in Fig. 7–21, is called a **block and tackle**. They are drawn this way although they are more likely to look like Fig. 7–22. Study Example 4 at the right.

7–19 Compound machines are made up of simple ones. The mechanical device

EXAMPLE 4

Find the ideal and actual MA's and the efficiency of the pulley system shown in the diagram.



Given: Data in diagram

To find: Ideal MA, actual MA, efficiency

Solution: Ideal MA = 4.0 (The rope down at the right merely changes the direction for convenience. It does not support the load,) Answer

$$\text{actual MA} = \frac{F_o}{F_i}$$

$$= \frac{1000\text{ kgf}}{400\text{ kgf}}$$

$$= 2.5 \text{ Answer}$$

$$\text{efficiency} = \frac{\text{actual MA}}{\text{ideal MA}}$$

$$= \frac{2.5}{4.0}$$

$$= 63\%, \text{ Answer}$$

Figure 7–21 What is the ideal MA of each of these pulley systems?

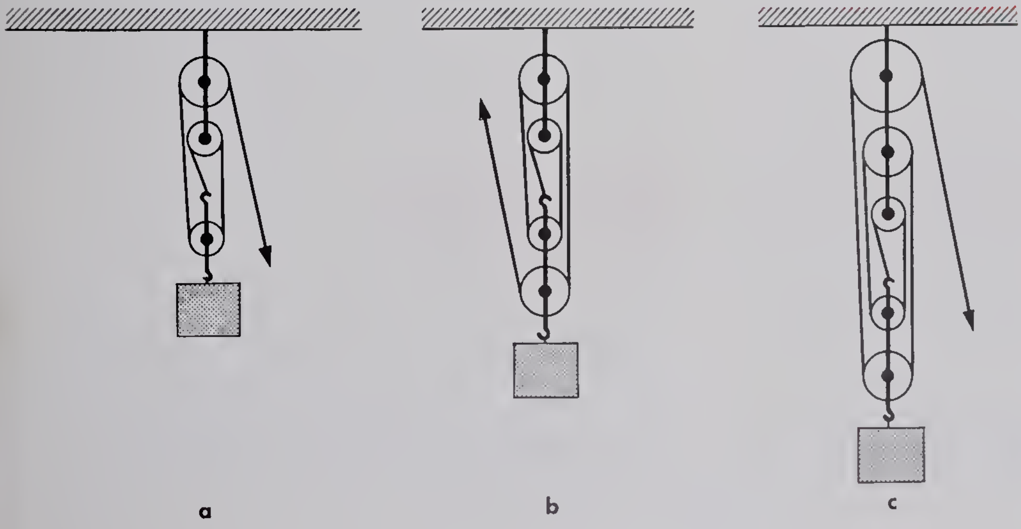


Figure 7–22

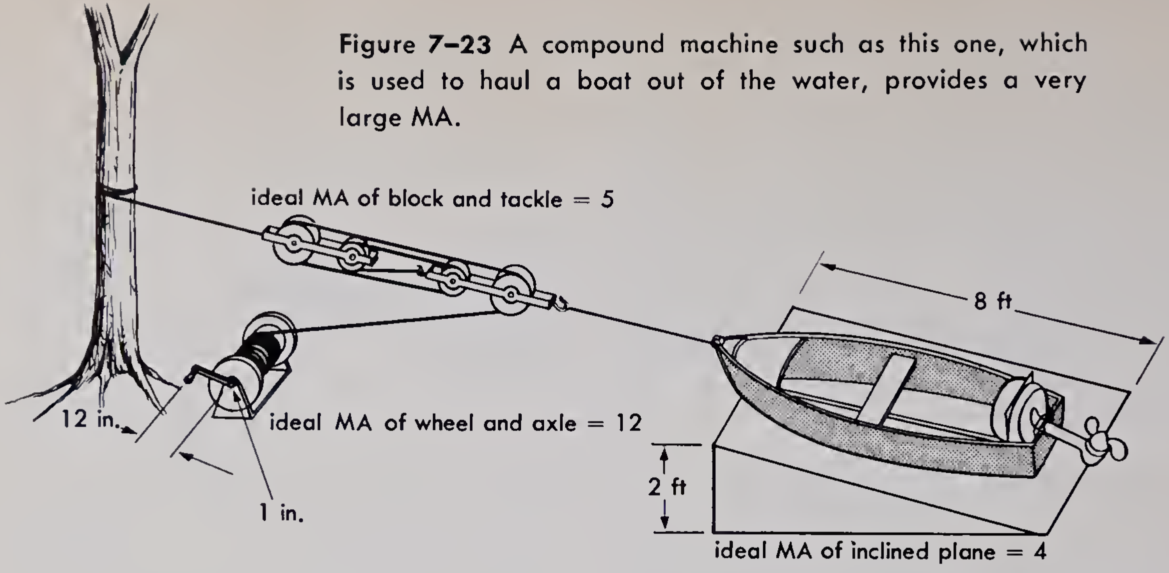

ideal MA of block and tackle = 5
8 ft
12 in.
ideal MA of wheel and axle = 12
2 ft
1 in.
ideal MA of inclined plane = 4

Figure 7–23 A compound machine such as this one, which is used to haul a boat out of the water, provides a very large MA.

in Fig. 7–23 includes an inclined plane, a pulley system, and a windlass. A device such as this that combines two or more simple machines is called a **compound machine.**

The total mechanical advantage of such a compound machine is equal to the product of the MA's of each of the several simple machines involved. In this case the ideal MA is 4 (for the plane) × 5 (for the block and tackle) × 12 (for the windlass), or 240. If the efficiency of the plane is 50%, that of the pulleys 90%, and that of the windlass 80%, then the overall efficiency is the product of these: $0.50 \times 0.90 \times 0.80 = 0.36$, or 36%. Therefore the actual MA of the system as a whole is 0.36×240, or 86.

7–20 What is a machine? This question was asked at the beginning of the discussion of machines. By now you should have a clearer understanding of what a physicist means by this term. A machine is a mechanical device that makes it possible to do work more conveniently. The machine itself is not a source of energy. Rather work is fed into it, and the machine changes the work in one of three ways:

1. The direction of the force may be changed, so that it is more convenient to apply. With the single fixed pulley, for example, you can raise a load by pulling down instead of up. In this case the mechanical advantage is 1.
2. The magnitude of the force may be changed, so that a small input force can be used to overcome a large output force. The inclined plane is usually used in this way, and so are most pulley systems, the wheel and axle, and many levers, such as the wrecking bar. In this case the mechanical advantage is greater than 1.
3. The magnitude of the force may be decreased in order that speed or distance may be increased. This is the situation with a fishpole, egg beaters, and a bicycle. Here the mechanical advantage is less than 1.

Most machines use the principle of the inclined plane or the lever, although some cannot be analyzed in this way.

Self Check

1. What is the ideal mechanical advantage of a lever?
2. What must you know about a wheel and axle in order to calculate its ideal MA?
3. What is the mechanical advantage of a single fixed pulley?

4. In what way is a single fixed pulley useful?
5. What is an easy way in which to determine the ideal MA of a block and tackle?
6. How is the mechanical advantage of a compound machine determined?
7. In what way is a machine with a mechanical advantage less than 1 useful? with a mechanical advantage greater than 1?

Problems

Ⓐ **1.** The tinsnips of Fig. 7–15a have handles 10.0 in long and the person who uses them applies the force 1.0 in from the end of the handle. What is the mechanical advantage when the blades are cutting a piece of metal placed 0.50 in from the fulcrum? How can the operator increase the mechanical advantage? How can he decrease the mechanical advantage?

2. The handles of a nutcracker are 15 cm long. How much force do you exert on a nut placed 3.0 cm from the hinge if you push with a force of 20 N at the end of the handles?

3. What is the mechanical advantage of the fishpole of Fig. 7–15f if the pole is 8.0 ft long and the distance between the fisherman's two hands is 1.0 ft? What is the heaviest fish he can lift if he applies an upward force of 20 lb while keeping the hand at the end of the pole stationary? How could he make it easier to lift a fish?

4. What is the ideal mechanical advantage of a wheel and axle if the diameter of the axle is 4.0 cm and the length of the crank is 30.0 cm?

5. A wheel and axle has an ideal MA of 20. What is its efficiency if a force of 3.0 kgf on the crank will lift a load of 40.0 kgf?

6. What is the ideal MA of each of the pulley systems of Fig. 7–21?

7. Draw a pulley system with an ideal MA of 6.

8. The pulley system of Problem 7 is used to raise a load of 500 kgf. What force is required if the friction is ignored?

9. If the pulley system of Problem 7 is 90% efficient, what force will be required to lift a load of 500 kgf?

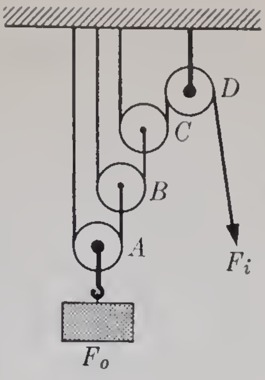


Figure 7–24

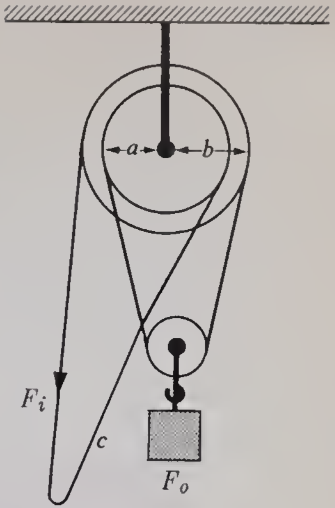


Figure 7–25

10. If the load is raised 2.0 m by the pulley system of Problem 7, how many meters of rope will have to be pulled down by the operator?

Ⓑ **11.** What is the ideal MA of the pulley system of Fig. 7–24? You cannot figure it by counting cords. Start with output force (F_o) and figure the tension in the ropes supporting pulley *A*. Then repeat for pulley *B*, and so on.

12. Figure 7–25 is a diagram of a differential pulley or chain hoist used to lift very heavy loads. The two pulley wheels at the top are rigidly fastened together so that they rotate at the same rate. The wheels have teeth that engage the links of the chain so that it cannot slip. The input force is applied as shown. The part of the chain marked *c* exerts a negligible force. Think of the upper pair of pulleys as a lever and show that the ideal MA of the system is $\frac{2b}{b-a}$, where *b* is the radius of the larger top pulley and *a* is the radius of the smaller one.

Discussion Questions

1. Why do ballplayers hold their hands close together on the bat to hit a home run and far apart for a bunt?
2. In addition to friction, a block and tackle has another important cause of inefficiency. What is it? How can this cause be minimized?

3. A machine for lifting weights consists of a sealed box suspended from above. Two ropes hang down from the box, coming out through holes in the bottom. You are assigned the problem of determining which rope should be used for the weight and of determining the ideal and actual MA's of the machine. How could you do it?

Chapter Summary

Friction is a force that exists between surfaces. It opposes the motion of one surface over another largely because of attraction of the surfaces for each other, but also because of irregularities in the surfaces. The magnitude of the force of friction is directly proportional to the force pressing the surfaces together and depends on the nature of the surfaces and the kind of motion. In general, it is independent of overall area. Starting friction is greater than sliding friction, which in turn is greater than rolling friction. Friction decreases slightly as the speed goes up, except when the speed is extremely slow. The laws of friction are empirical laws and are approximately true. Work done to overcome friction is largely converted to heat energy. The coefficient of friction is the ratio between frictional force and the force pressing the sliding surfaces together.

A machine is a mechanical device that makes it possible to do work more conveniently by changing the applied force in direction or in magnitude or both. Most complex machines are combinations of simple ones that may be classified as either inclined planes or levers. The law of conservation of energy applies to machines. The work input must be equal to the work output plus the energy wasted in overcoming friction or in other ways. The ratio of output force to input force for a machine is called its actual mechanical advantage. The ideal mechanical advantage is the mechanical advantage of a machine that wastes no energy; it can be calculated from the geometry of the machine. The efficiency of a machine is the ratio of the useful work output to the total work input. It can also be calculated from the actual and ideal mechanical advantages. The loading ramp, wedge, and screw are forms of inclined planes. The law of moments can be applied to a study of levers. Many simple tools are levers. The wheel and axle and the pulley may be considered kinds of levers. A machine with a mechanical advantage greater than 1 multiplies the applied force; one with a mechanical advantage less than 1 multiplies the speed of the operation; and one with a mechanical advantage of 1 simply changes the direction of the force.

Vocabulary

machine (*p. 165, 173*)
stick-slip (*p. 166*)
force of friction (*p. 167*)
sliding friction (*p. 168*)
starting friction (*p. 169*)
rolling friction (*p. 169*)
laws of friction (*p. 170*)
empirical laws (*p. 170*)
normal force (*p. 171*)
coefficient of friction (*p. 172*)
work input and output (*p. 173*)
law of work (*p. 174*)
input force; output force (*p. 174*)
mechanical advantage, actual and ideal (*p. 175*)
input distance; output distance (*p. 175*)
efficiency (*p. 175*)
inclined plane, wedge; screw (p. *176*)
lever; wheel and axle; pulley; block and tackle (*p. 178*)
input arm; output arm (*p. 179*)
block and tackle (*p. 183*)
compound machine (*p. 184*)

Problems

A 1. A 2.0-lb block sliding across a floor at 20 ft/sec. comes to rest in 5.0 sec. What is the coefficient of friction?

2. How long should a ramp be in order that a 20-kgf force can be used to push a wheelchair up the ramp to a height of 4.0 m if the wheelchair and occupant weigh 120 kgf and friction is ignored?

3. How long should the ramp of Problem 2 be if there is a frictional force of 4 kgf and if the total force to push the wheelchair is still to be 20 kgf?

4. An inclined plane 24.0 m long and 3.0 m high has an efficiency of 80%. What force is required to move a load weighing 750 N up the slope?

5. What is the force of friction in Problem 4?

6. A jackscrew has an efficiency of 16%. What must be its ideal MA if a force of 200 lb is to be used to raise a 10-ton load?

7. A wrecking bar 120 cm long is used to pry up a 200-kgf rock. If the fulcrum is 20 cm from the rock, what input force must be supplied? What is the MA of the bar?

8. Where should the fulcrum of the wrecking bar 120 cm long be placed in order for an input force of 25 kgf to pry up the 200-kgf rock?

9. A wheel and axle with a crank 20 cm long has an axle diameter of 3.2 cm. A force of 330 gf on the crank will lift a load of 3.0 kgf. What is the efficiency of the machine?

10. A block and tackle with an ideal MA of 8.0 and an efficiency of 85% is used to pull a boat up a ramp that rises 1.0 ft for a length of 20 ft. The efficiency of the ramp is 50%. What is the actual MA of the system?

11. By pulling down 24 m of rope from a block and tackle, you find that you can lift a load 75 cm. You exert a force of 50 kgf and lift a load of 1400 kgf. Find the efficiency of the block and tackle.

B **12.** By solving the problem with algebraic symbols prove that it was not necessary in Problem 1 to know the mass of the block.

13. Design a compound machine that will get a 2000-lb boat from the water into a boathouse, the floor of which is 4.0 ft above the water. The input force is to be no more than 40 lb and the overall efficiency of the machine may be assumed to be 25%.

Discussion Questions

1. What is the direction of the force of friction between two surfaces when one surface is moving to the right and the other is moving to the left?

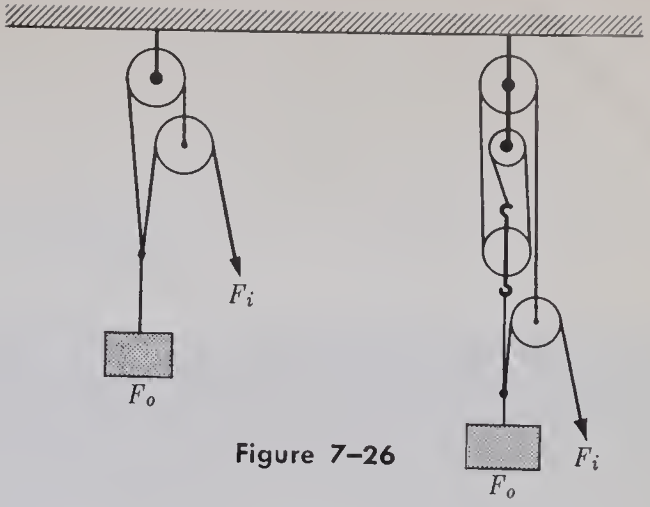


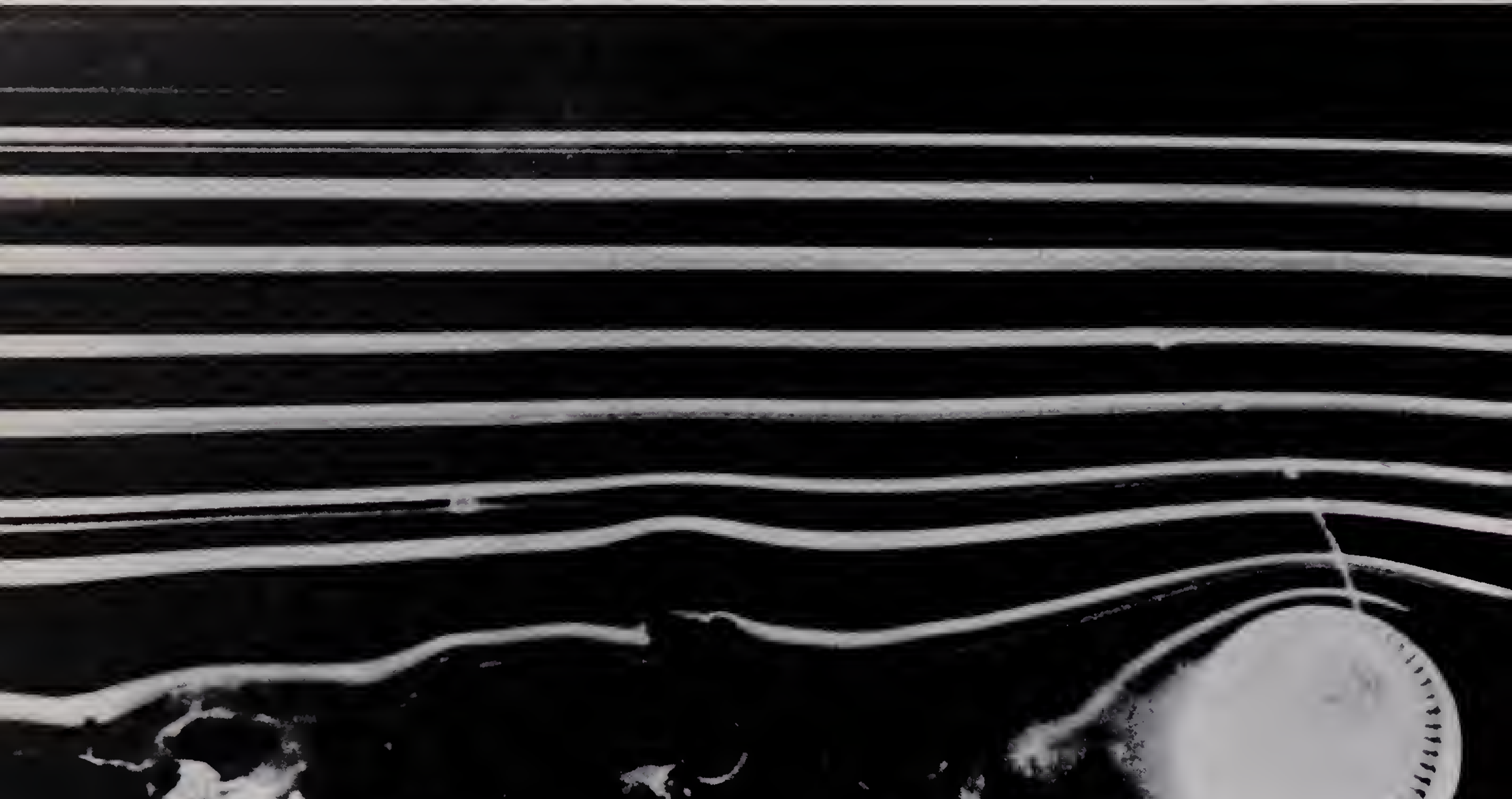
Figure 7–26

2. Why does it sometimes help when you move a heavy piece of furniture to put a rug under it?
3. When you pull a sled or wagon, you usually exert a force at an angle to the horizontal. What effect does this have on the frictional force?
4. If you were trying to raise the corner of a building with a jack and you were not quite strong enough to do it, how could you increase the MA of the jack?
5. The pulley arrangements of Fig. 7–26 sometimes seem to have an efficiency that is greater than 100%. That is, the weight times the height it is lifted is greater than the input force times the input distance. Can you think of an explanation?

Work On Your Own

1. All the illustrations showing bricks being pulled in order to investigate the force of friction (Fig. 7–4 through 7–7) showed the force being supplied horizontally. If the force is supplied at an angle upward, the force pressing the surfaces together decreases and therefore the force of friction decreases. However the horizontal component of the force in the cord also decreases. This raises a question: If you pull at an upward angle, must you pull with a greater force than if you pull horizontally, with the same force, or with a smaller force? Is the answer the same for all angles? Investigate experimentally and, if you are good at trigonometry, try for a mathematical solution.
2. Build a compound machine and calculate its ideal and actual mechanical advantage.

CHAPTER 8



Courtesy of Professor Frank Brown, University of Notre Dame and courtesy of the science supplement of *Saturday Review.*

This baseball in a wind tunnel is spinning counterclockwise and is curving in the direction of its spin (toward the top of the tunnel). Its motion is the result of forces in a fluid — air.

Forces in Fluids

A little girl in the third grade was taking an intelligence test. She was marking a set of true-false statements. "Iron floats," said the statement. "True," wrote the little girl. Since the child did well on the test, the teacher asked her why she had said that it is true that iron floats. "I saw a ship in the river, and it was iron, and it floated," was the reply. This is certainly a reasonable answer, yet you know that a piece of iron dropped into a pan of water will sink to the bottom. How, then, does a ship float? And, for that matter, how does an airplane, much heavier than the air in which it travels, manage to stay up (Fig. 8–1)? Similar though these questions may sound, the answers to them are quite different. These answers are discussed in this chapter. They concern the behavior of liquids and gases, materials that flow and that are therefore called fluids (see opposite page).

Liquids Exert Pressure

8–1 Specific gravity is an important property. If you throw a stone into a pond, it sinks. Probably if someone asked you why the stone sinks, you would say, "Because it's heavier." Just what do you mean by that? The weight of the stone might be about a pound. Does the water in the pond, then, weigh less than a pound? Obviously not. It probably weighs many tons. The trouble comes in comparing the weight of a small stone with the weight of a much larger volume of water. For the comparison to be meaningful, you must compare the weights of equal volumes of the stone and the water.

A cubic centimeter is a convenient volume for comparison. When you studied the metric system, you learned that a cubic centimeter of water has a mass of almost exactly 1 g (p. 32). Therefore, at sea level on the earth, it weighs 1 gf. If you were to measure the weight of a cubic centimeter of the stone, you might find that it was 2.5 gf. Thus for equal volumes, the stone is 2.5 times as heavy as water. It is customary to compare weights of various substances with the weight of an equal volume of water. The ratio of the weights is called the **specific gravity**.

$$\text{specific gravity of an object} = \frac{\text{weight of the object}}{\text{weight of an equal volume of water}}$$

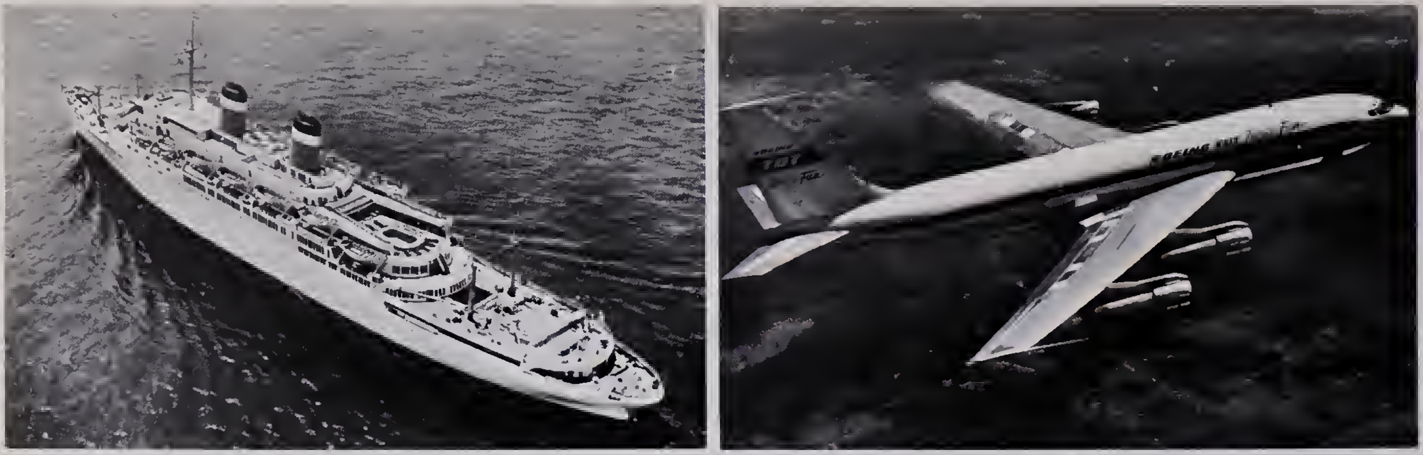


Figure 8–1 Ships and planes are heavier than the fluids through which they travel. How do they stay up?

Since the volume of water changes as the temperature changes, for very accurate work the weight of water at 39.2° F is used and the temperature of the object is also stated.

In what units is specific gravity expressed? In the case of the stone just discussed, when the volume is 1.0 cm³, the weight is 2.5 gf. The weight of an equal volume of water is 1.0 gf. Therefore:

$$\text{specific gravity} = \frac{2.5 \text{ gf}}{1.0 \text{ gf}} = 2.5$$

Specific gravity is a number and is given without units. The specific gravities of various materials are given in Table 8–1 at the right.

Do It Now

1. In Table 8–1 find a liquid that will form a layer on top of water.
2. In Table 8–1 find a wood that will sink in water.

Table 8–1 SPECIFIC GRAVITIES OF CERTAIN MATERIALS AT ORDINARY ATMOSPHERIC TEMPERATURES

Material	*Specific gravity*
Liquids	
Water (at 39.2°F)	1.0000
Water (at 68.0°F)	0.9982
Sea water	1.025
Gasoline	0.66–0.69
Mercury	13.6
Solids	
Granite	2.60–2.76
Sandstone	2.14–2.36
Balsa wood	0.11–0.14
Maple wood	0.62–0.75
Ebony wood	1.11–1.33
Copper	8.9
Lead	11.3

8–2 There are two types of density. A cubic centimeter of water has a mass of 1 g. Therefore the mass density (d_m) of water is 1 gram per cubic centimenter (1 g/cm³). **Mass density** is defined as the mass per unit volume of a substance. In mathematical form:

$$\text{Mass density} = \frac{\text{mass of an object}}{\text{volume of the object}}$$

$$d_m = \frac{m}{V}$$

Unlike specific gravity, density is stated in units. In the metric system, density is usually given in grams per cubic centimeter. Notice that when these units are used, the mass density is *numerically* equal to the specific gravity.

If the mass density of water is 1 g/cm³, then at sea level on the earth its weight density (d_W) is 1 gram of force per cubic centimeter (1 gf/cm³). **Weight density** is defined as weight per unit volume of a substance:

$$\text{Weight density} = \frac{\text{weight of an object}}{\text{volume of the object}}$$

$$d_W = \frac{W}{V}$$

Since weight varies from place to place, the weight density also varies, but the mass density does not. At the surface of the moon, the mass density of water would still be 1 g/cm³, but its weight density would be only 0.17 gf/cm³, approximately one sixth as much. The weight density of water at the surface of the earth in English units is 62.4 lb/ft³.

Given the density of water and of some other substance, you can easily find the specific gravity of the other substance. Since density is the weight of a particular unit of volume, the volumes are equal. Therefore:

$$\text{Specific gravity of X} = \frac{\text{density of X}}{\text{density of water}}$$

8–3 Pressure is force per unit area. A hunting knife is light and easy to hold when you grasp it by the handle, but if you try to balance it with the point down on your hand, you will find the experience a painful one. The force on your hand is the same in both cases. It is equal to the weight of the knife. The difference is in the pressure.

Suppose a table weighs 60 lb. Then each of its four legs exerts a force of 15 lb on the floor underneath. If the area of the bottom of each leg is 2.0 in², then the force of 15 lb is distributed over an area of 2.0 in², providing a force of 7.5 lb on each square inch.

To protect the rug a caster cup may be put under each leg. If the area of contact is increased to 5 in² by the caster cup, the force per square inch becomes 15 lb divided by 5 in² or 3 lb/in².

When you calculate the force on a unit of area (1 in², in this case), you are calculating pressure. **Pressure** is a derived unit and is defined as the force per unit area.

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$P = \frac{F}{A}$$

You can use the equation for pressure to find total force when the pressure and area are known. For example, a layer of water 1 in deep exerts a pressure of 5.2 lb/ft². The total force on a pavement with an area of 60 ft² is:

$$F = PA$$

$$= 5.2\ \frac{\text{lb}}{\text{ft}^2} \times 60\ \text{ft}^2 = 3.1 \times 10^2\ \text{lb}$$

8–4 Pressure increases with depth. You often read of the great pressure that must be withstood by the hulls of submarines or by the suits of deep-sea divers. Anyone who has swum underwater knows that the pressure at a depth of even a few feet is quite noticeable, especially in the ears. In fact, unless one is an experienced swimmer, he will be distinctly uncomfortable at depths of more than 10 or 15 ft.

Careful measurements show that the pressure in a liquid is directly proportional to depth. This is not surprising, for the pressure at any point in a liquid is due to the weight of the liquid above that point. This suggests a method for finding the pressure at any depth in a liquid. For example, suppose you want to know the pressure in pounds per square foot at a depth of 20.0 ft in a lake. This is the same as the weight of

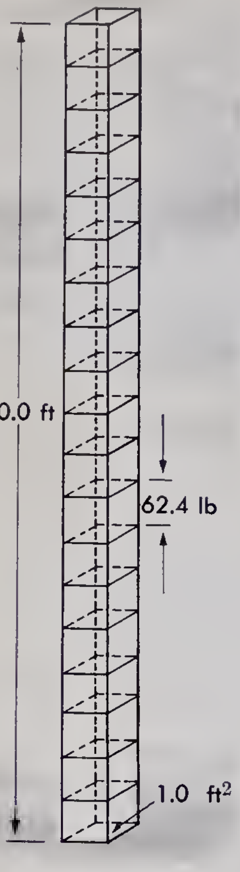


Figure 8–2 The pressure per square foot at a depth of 20.0 ft in water is equal to the weight of a column of water 20.0 ft high and having a cross-sectional area of 1.0 ft². Here you might think of the column as being made of 20 cubes of water stacked up. Each of them weighs 62.4 lb, making the total weight 62.4 × 20.0, or 1248 lb.

a column of water 20.0 ft high standing on 1 ft² of lake bottom (Fig. 8–2).

The column of water is at the surface of the earth. Therefore each cubic foot of water weighs 62.4 lb, and 20 of them stacked up will weigh 20 times 62.4, or 1.25×10^3 lb. Therefore the pressure is 1.25×10^3 lb/ft². In general:

$$\text{Pressure (in a liquid)} = hd_W$$

where h is the height of the liquid and d_w is its weight density. In the case of the lake, the pressure 20 ft down is

$$P = h \times d_W$$

$$= 20.0 \text{ ft} \times 62.4 \frac{\text{lb}}{\text{ft}^3} = 1.25 \times 10^3 \text{ lb/ft}^2$$

If you want the pressure in pounds per square inch, you can convert it thus:

$$P = \frac{1.25 \times 10^3 \text{ lb}}{\text{ft}^2} \times \frac{1 \text{ ft}^2}{144 \text{ in}^2} = 8.68 \text{ lb/in}^2$$

Notice that the formula for pressure ignores air pressure. That is, it assumes that the pressure at the surface of the water (where $h = 0$) is zero. Actually, of course, the pressure at the surface is equal to atmospheric pressure, which varies with the weather, but which is approximately 14.7 lb/in² at sea level. Therefore the total pressure at the bottom of 20.0 ft of water is 8.7 lb/in² plus 14.7 lb/in², or 23.4 lb/in². The total pressure, combining the atmospheric pressure and the pressure of the fluid being measured, is called the **absolute pressure**. The **gauge pressure**, measured by a gauge (on the tires of a car, for example), is the difference between the pressure of the atmosphere and the pressure of the fluid being measured. In most situations the gauge pressure is the useful measurement. An engineer designing a water supply system would want to know how much greater than the pressure of the atmosphere is the pressure of the water, for this is the pressure that determines how fast the water will flow from the faucets. A submarine has approximately normal air pressure inside it so the total force which must be resisted by its sides is due to the gauge pressure of the water. Study Examples 1 and 2 on the next page.

8–5 Pressure is important in water storage and supply. Any device intended for use underwater must be designed to withstand water pressure. The greater the depth of water involved, the greater is the pressure. A good example of this is the case of dams; they are made very thick at the bottom where the pressure is the greatest, and thinner toward the top.

When a water faucet is opened, the water does not simply fall out. It is forced out by the pressure inside the system. One way to

EXAMPLE 1

A rectangular tank 30.0 ft wide and 40.0 ft long is filled with water to a depth of 10.0 ft. Find the pressure at the bottom of the tank in lb/in^2 and the total force on the bottom in lb.

Given: Width = 30.0 ft; length = 40.0 ft; $h = 10.0$ ft

To find: P, F

Solution: $P = hd_W$

$$= 10.0\ \text{ft} \times 62.4\ \frac{\text{lb}}{\text{ft}^3}$$

$$= 624\ \text{lb/ft}^2$$

$$= \frac{624\ \text{lb}}{\text{ft}^2} \times \frac{1\ \text{ft}^2}{144\ \text{in}^2}$$

$$= 4.33\ \frac{\text{lb}}{\text{in}^2},\ \text{Answer}$$

$$F = PA$$

$$= 624\ \frac{\text{lb}}{\text{ft}^2} \times 30.0\ \text{ft} \times 40.0\ \text{ft}$$

$$= 7.49 \times 10^5\ \text{lb, Answer}$$

The total force on the bottom is also equal to the weight of all of the water. Therefore the problem can be checked as follows:

$$d_W = \frac{\text{weight of water}}{\text{volume of water}}$$

$$62.4\ \frac{\text{lb}}{\text{ft}^3} = \frac{\text{weight of water}}{30.0\ \text{ft} \times 40.0\ \text{ft} \times 10.0\ \text{ft}}$$

$$\text{weight of water} = 62.4\ \frac{\text{lb}}{\text{ft}^3} \times 30.0\ \text{ft} \times 40.0\ \text{ft} \times 10.0\ \text{ft}$$

$$= 7.49 \times 10^5\ \text{lb} \quad \text{Check}$$

EXAMPLE 2

Find the pressure at the bottom of a tank of gasoline 12 m deep. The specific gravity of gasoline is 0.68.

Given: $h = 12\ \text{m} = 1.2 \times 10^3\ \text{cm}$
specific gravity of gasoline = 0.68

To find: P

Solution: $$\text{Specific gravity} = \frac{\text{density of substance}}{\text{density of water}}$$

In this definition, the densities can be either mass densities or weight densities as long as both are the same kind. Therefore:

$$0.68 = \frac{d_W}{1.0\ \text{gf/cm}^3}$$

$$d_w = 0.68\ \text{gf/cm}^3$$

$$P = hd_w$$

$$= 1.2 \times 10^3\ \text{cm} \times 0.68\ \text{gf/cm}^3$$

$$= 8.2 \times 10^2\ \text{gf/cm}^2$$

provide this pressure is to store water in reservoirs on hills or mountains. Pipes carry the water to cities at a lower elevation, and the pressure is due to the difference in height. When a mountain reservoir is not possible, water may be pumped into a storage tank. The pressure in the water system is due to the height of the water in the tank above the point where it is being used. Tall buildings and factories frequently use one or more of these gravity-feed tanks in their water supply systems.

Whether the pressure is due to the elevation of a reservoir or to the height of water in a storage tank, the pressure at the faucet is somewhat less than that indicated by the formula $P = hd_W$ because of internal friction of the water flowing through the pipes.

Another way to provide pressure in a water system for homes is to use a pressure tank. Here water is pumped into a sealed storage tank. As the water is pumped in, the air trapped in the tank is compressed and provides pressure for the water system. This is due to the fact that gases are more easily compressed than liquids. An automatic control turns the pump motor on when the pressure in the tank falls to a certain value, and turns it off again when

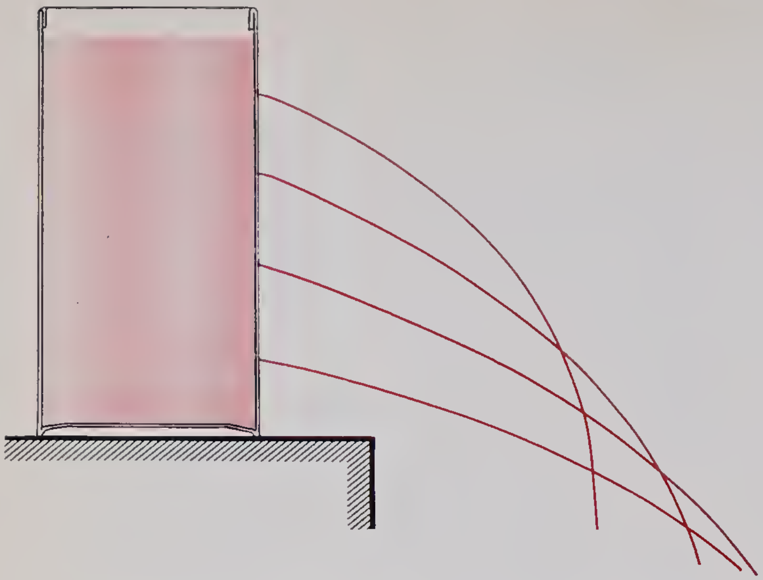


Figure 8–3 This diagram shows (1) that liquid pressure is exerted sideways, among other directions, and (2) that the magnitude of the liquid pressure increases with depth.

the proper operating pressure has been restored. Pressure-tank systems are commonly used in very small installations, such as a remote farm or other private dwellings away from a public water supply.

8–6 Liquid pressure exerts equal force in all directions. If you punch holes in the side of a tin can and then fill it with water, you find that the water squirts horizontally out of the holes (Fig. 8–3). This shows that the force due to pressure in a liquid is exerted horizontally as well as down. The fact that the water coming from the lowest hole is more nearly horizontal than the others shows that the pressure there is the greatest.

If you punch a hole in the bottom of a tin can and then push the can bottom down into a pail of water, water spurts up through the hole, showing that the force due to pressure in the water is also exerted upward.

The simple apparatus illustrated in Fig. 8–4 can be used to show that the force due to pressure at a single point in a liquid is the same in all directions.

How can you calculate the force on the side of a container of a liquid? This is easy to do if the side is the same width all the way down, as in a rectangular tank. Since the pressure increases steadily with depth, the average pressure is the pressure halfway down. Consider the tank of Example 1 (p. 193). It is 30.0 ft wide, 40.0 ft long, and 10.0 ft deep. To find the force on the long side, first find the pressure half-way (5.0 ft) down:

$$P = hd_W$$

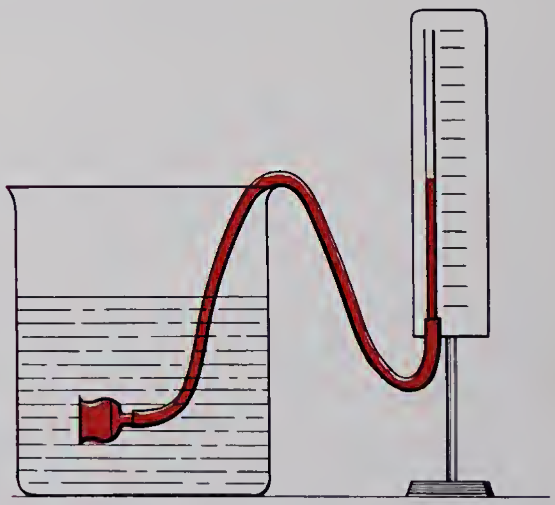
$$= 5.0\ \text{ft} \times 62.4\ \frac{\text{lb}}{\text{ft}^3} = 3.1 \times 10^2\ \text{lb/ft}^2$$

The area of the long side is 10.0 ft × 40.0 ft, or 400 ft². Therefore:

$$F = PA$$

$$= 3.1 \times 10^2\ \frac{\text{lb}}{\text{ft}^2} \times 400\ \text{ft}^2 = 1.2 \times 10^5\ \text{lb}$$

Figure 8–4 This apparatus has a rubber diaphragm over the mouth of a thistle tube connected to a vertical glass tube. Water pressure on the diaphragm causes colored water in the apparatus to rise. Lowering the thistle tube shows that pressure increases with depth. Changing the direction of the thistle tube shows that the force due to pressure is the same in all directions at the same depth.



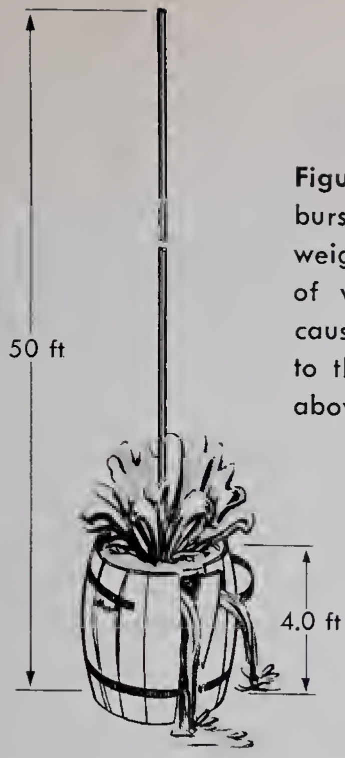


Figure 8–5 The barrel bursts, not because of the weight of the 80 gallons of water in it, but because of the pressure due to the water in the pipe above it.

8–7 Pressure is transmitted throughout a liquid. Look at the 80-gallon barrel of Fig. 8–5. It is more than strong enough to be filled to the brim with water without bursting. Then a tight lid is put on and a long pipe inserted in it. When the pipe is filled with one gallon of water, the added pressure bursts the barrel. In order to understand this, think about the pressure on the bottom of the barrel at a point right below the hole where the pipe is placed. First calculate the pressure when there is no water in the pipe:

$$
\begin{aligned}
P &= hd_W \\
&= 4.0\ \mathrm{ft} \times 62.4\ \frac{\mathrm{lb}}{\mathrm{ft}^3} = 2.5 \times 10^2\ \mathrm{lb/ft}^2 \\
&= 1.7\ \mathrm{lb/in}^2
\end{aligned}
$$

Now calculate the pressure when the pipe is full of water. The water over the spot in the bottom of the barrel is now 50.0 ft deep. Therefore:

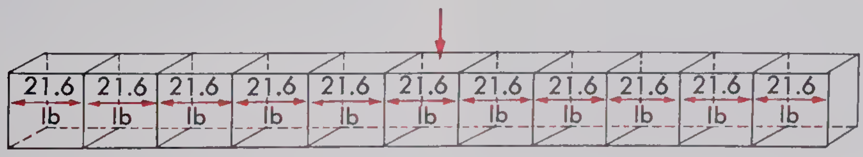
$$
\begin{aligned}
P &= hd_W \\
&= 50.0\ \mathrm{ft} \times 62.4\ \frac{\mathrm{lb}}{\mathrm{ft}^3} = 3.12 \times 10^3\ \mathrm{lb/ft}^2 \\
&= 21.6\ \mathrm{lb/in}^2
\end{aligned}
$$

The amazing conclusion is that adding one more gallon to the 80 already present has made the pressure more than 10 times as great.

So far, however, this is merely the pressure on a small spot at the bottom of the barrel. What about the sideways pressure? You know from the experiment of Fig. 8–4 that the force due to pressure is the same in all directions at a single point in a liquid. Therefore there is a force of 21.6 lb directed sideways on each square inch of water to the right and left of the central spot. Think of the water at the bottom of the barrel as a collection of 1-in cubes, as shown in Fig. 8–6. The central cube is the one directly under the pipe. The force exerted on it is 21.6 lb, and, in its turn, it exerts a force of 21.6 lb to the right and left. As a result, the next cubes push the ones beyond them with a force of 21.6 lb. This continues out to the edge of the barrel. The barrel was built to stand a pressure of 3 or 4 lb/in^2, but not one as much as 21.6 lb/in^2. It bulges at the seams and out comes the water.

The situation in the barrel is an illustra-

Figure 8–6 The water at the bottom of the barrel of Fig. 8–5 may be thought of as consisting of a large number of 1-in cubes. The pressure at the bottom is 21.6 lb/in^2. This produces a force of 21.6 lb on each square inch in all directions and the force is transmitted from cube to cube out to the edge of the barrel.



tion of Pascal's principle, named for the French scientist who first stated it. **Pascal's principle** says that if pressure is exerted on a confined liquid, the pressure is transmitted in all directions without loss. This does not mean that the pressure is the same everywhere in the liquid. What it does mean is that any pressure added from outside is added everywhere. In the case of the barrel the pressure on the bottom without water in the pipe was 1.7 lb/in^2. With the extra water it is 21.6 lb/in^2. The added pressure is 21.6 lb/in^2 − 1.7 lb/in^2, or 19.9 lb/in^2. The pressure at the bottom of the barrel is always greater than that at the top, but when water is poured into the pipe, the extra 19.9 lb/in^2 pressure is added both at the top of the barrel and at the bottom.

The fact that adding a small amount of water, 1 gallon in this case, to the water in the barrel can raise its pressure by a very large amount when the water is in a small pipe is so strange that it is often referred to as the "hydrostatic paradox."

One of the puzzling aspects of the hydrostatic paradox is that the total force on the bottom of the barrel is as great as it would be if the barrel were 50 ft tall and filled with water. What is the source of all this extra force? The weight of one added gallon of water in the pipe is not enough to account for it. Here you need Pascal's principle plus Newton's third law to help you understand what is happening. According to the principle, the pressure due to the water in the pipe is transmitted equally in all directions, including upward. Therefore the water exerts a large upward force on the top of the barrel. Now, unless the top of the barrel breaks, the top exerts an equal and opposite downward force on the water, and this force is transmitted through the water to the bottom of the barrel. The water in the tall pipe is the cause of the increase in pressure, but the third-law reaction force of the wood of the barrel top is the cause of the large force on the bottom.

Do It Now

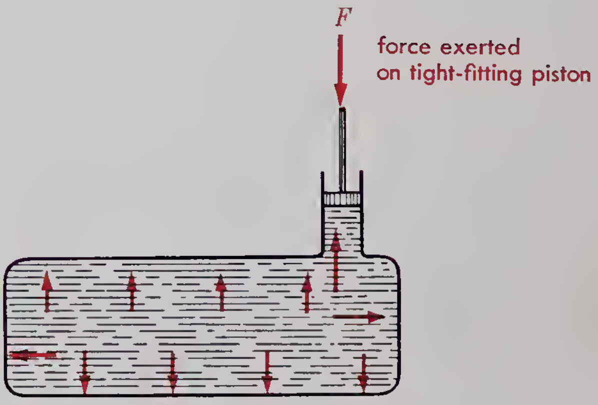
If you were to put the barrel and pipe of Fig. 8–5 on the scales when it was empty and when it was full to the 50-ft mark, would the added weight on the scale be equal to the added force on the bottom of the barrel?

8–8 The hydraulic press employs Pascal's principle.

The liquid in Fig. 8–7 is under pressure due to the force exerted on the piston. According to Pascal's principle, this pressure is transmitted without loss in all directions. Now even in a closed system such as this, there are differences in pressure due to differences in depth at different parts of the system. However, if these differences are slight compared with the pressure caused by the force on the piston, they may be ignored. Therefore, in a closed body of liquid under high internal pressure, the pressure at all points is essentially the same. The automobile lift in a garage operates on this principle.

Such a system is called a **hydraulic press** To see how it works, consider a press in

Figure 8–7 If a liquid is completely enclosed and if it is subjected to an outside force, the pressure is increased equally in all parts of the liquid.



which the smaller piston has a cross-sectional area of 1.0 in^2 and the larger one an area of 100 in^2. What happens if a force of 80 lb is applied to the smaller piston? First calculate the pressure at the small piston:

$$P = \frac{F}{A} = \frac{80 \text{ lb}}{1.0 \text{ in}^2} = 80 \text{ lb/in}^2$$

This pressure is large compared with the pressure due to depth in the system and it is transmitted without loss in all directions. Therefore the pressure on the large piston is also 80 lb/in^2. The total force on the large piston is given by:

$$F = PA$$

$$= 80 \frac{\text{lb}}{\text{in}^2} \times 100 \text{ in}^2 = 8.0 \times 10^3 \text{ lb}$$

Thus you see that when a force of only 80 lb is applied to the small piston, there is a force of 8,000 lb on the large piston. This is the type of result you obtained earlier with the simple machines of Chapter 7. The hydraulic press is another kind of simple machine. Its mechanical advantage is calculated in the usual way:

$$MA = \frac{F_o}{F_i}$$

$$= \frac{8.0 \times 10^3 \text{ lb}}{80 \text{ lb}} = 10^2$$

Self Check

1. What is meant by pressure?
2. Give an illustration to show that the same object can exert different amounts of pressure due to its weight alone.
3. Compare the pressure due to water at a depth of 10 yd with the pressure at 20 and at 30 yd.
4. The mass density of a certain rock is 4 g/cm^3 at the surface of the earth. Compare its mass density and its weight density at the surface of the moon.
5. The pressure due to the water at a certain depth in the ocean is 100 lb/in^2. Give the approximate value of the absolute pressure and tell why it is different.
6. The gauge pressure at point *A* in a tank of oil is 100 lb/in^2. The gauge pressure at point *B* is 120 lb/in^2. Air above the tank is now compressed so that it has a gauge pressure of 30 lb/in^2. What is now the gauge pressure at points *A* and *B*?
7. How can the average pressure on a vertical side of a tank be calculated?
8. What is Pascal's principle?
9. If the bottom of the piston shown in figure 5–7 has an area of 1.0 in^2, what would the pressure be at a point on the walls of the container when 10 lb. of force are applied to the piston?

Problems

Ⓐ **1.** A block of wood measures 20 cm by 30 cm by 10 cm and weighs 4200 gf. Find its weight density.

2. A skin-diver goes 100 ft below the surface of a fresh-water pond. What is the pressure at this depth in lb/ft^2 and lb/in^2?

3. What is the total force on one arm of the skin-diver in Problem 2 if the area is 240 in^2?

4. What is the pressure in gf/cm^2 and dynes/cm^2 at the bottom of a column of mercury 76 cm high? The density of mercury is 13.6 gf/cm^3.

5. A cylindrical water tank with a diameter of 10.0 ft is filled to a depth of 15.0 ft. What is the pressure on the bottom in lb/in^2? What is the total force on the bottom? What is the total force on the sides?

6. A fish that normally lives a mile down in the ocean has a body area of 1.00 ft^2. If such a fish is brought to the surface it is likely to rupture because the pressure inside its body is equal to the pressure to which it was subjected by the water in which it lived. Find the total force tending to cause it to rupture. Density of sea water is 64.0 lb/ft^3.

7. When the pipe of Fig. 8–5 is full of water, what is the upward pressure on the top of the barrel?

8. A pressure that can support a column of water 60 cm high can also support a column of salt solution 50 cm high. What is the density of the salt solution?

9. The pistons of a hydraulic press have areas of 5.0 cm^2 and 200 cm^2. If a force of 100 N is supplied to the smaller cylinder: (a) What is the pressure on the small cylinder? (b) What is the pressure on the large cylinder? (c) What is the load that can be lifted by the large cylinder?

10. A hydraulic press raises a load of 5,000 lb. when a force of 100 lb. is applied to the small piston. If the small piston has an area of 4.0 in^2, what is the area of the large piston? If the small piston moves 1.00 feet, how far would the large piston move? (Assume that friction is negligible).

11. The diameters of the cylinders of a hydraulic press are 20 mm and 10 cm. If 10.0 gf are applied to the small cylinder, what force is exerted on the large cylinder? If the smaller cylinder is pushed down 40 cm, how high will the larger cylinder rise? (Assume that friction is negligible).

B **12.** What must the air pressure be in a pressure tank if the water in the tank is 4.0 ft deep and the tank is to supply water to a faucet 100 ft above the bottom of the tank? Assume a pressure loss due to friction in pipes of 3.0 lb/in^2.

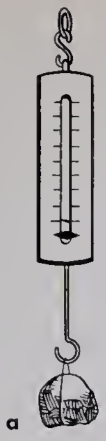
Discussion Questions

1. A small child often finds it less painful than an adult to walk barefoot. Aside from the fact that he may have toughened his skin by spending a lot of time without shoes, is there any reason why the child should not feel as much pain?
2. Which will exert a greater pressure on ice, dull skates or sharp ones?
3. In Fig. 8–3 you see water squirting from holes in a can. Where does the water get the energy to shoot out horizontally?

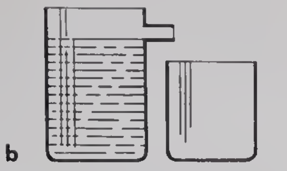
Buoyancy

8–9 A submerged object experiences an upward force. Anyone who has worked or played around water knows that objects seem to weigh less in water than they do in air. A boy who is removing a rock from a swimming hole may be able to raise the rock from the bottom of the pool to the surface of the water without trouble. However, as he tries to take it from the water, he finds that it is almost too heavy to carry. From this and similar experiences you learn that when objects are immersed in water or other liquids, they undergo an apparent loss of weight; this apparent loss is called **buoyancy**, or **buoyant force.**

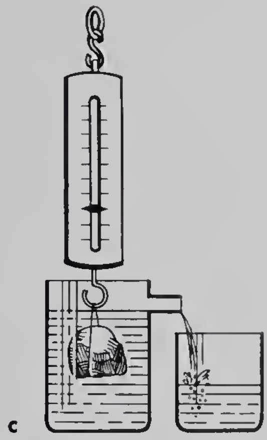
The magnitude of the buoyant force can be measured in a simple experiment, as shown in Fig. 8–8. From this experiment



An object is weighed in air. It weighs 100 gf.



A can is filled to the brim with water and a small can is weighed and placed ready to catch the water that overflows.



The object is now weighed when it is under water. It weighs 80 gf. The overflow can catches the water displaced by the object. The overflow can is weighed again and found to be 20 gf heavier than when empty. This is the weight of the water displaced by the object. It is also equal to the loss of weight of the object when it is immersed in water.

Figure 8–8 Experimental proof of Archimedes' principle.

you see that the loss of weight of an object immersed in water is equal to the weight of the water it displaces; this is called **Archimedes' principle**, named for the Greek scientist who first stated it clearly. According to this principle, an object immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced. (Note that the word "fluid" is used here, since the principle applies to gases as well as liquids.) Study Examples 3 and 4 on the right.

EXAMPLE 3

A stone weighs 250 gf in air and 150 gf in water. What is its weight density?

Given: Weight of stone in air = 250 gf
Weight of stone in water = 150 gf

To find: d_W of stone

Solution: Loss of weight of stone
= 250 gf − 150 gf
= 100 gf

Therefore weight of displaced water = 100 gf

Volume of displaced water = 100 cm^3, since 1 cm^3 of water weighs 1 gf

Volume of stone = 100 cm^3, since the stone did the displacing

$$\frac{\text{Weight of stone}}{\text{Volume of stone}} = \frac{250 \text{ gf}}{100 \text{ cm}^3}$$

$$= 2.50 \text{ gf/cm}^3, \text{ Answer}$$

EXAMPLE 4

A piece of metal weighs 20.0 lb in air and 18.0 lb in water. What is its specific gravity?

Given: Weight of metal in air = 20.0 lb
Weight of metal in water = 18.0 lb

To find: Specific gravity of the metal

Solution: Loss of weight of metal
= 20.0 lb − 18.0 lb
= 2.0 lb

This is the weight of the displaced water and is therefore the weight of an amount of water with the same volume as the metal.

Specific gravity

$$= \frac{\text{weight of an object}}{\text{weight of an equal volume of water}}$$

$$= \frac{20.0 \text{ lb}}{2.0 \text{ lb}}$$

$$= 10, \text{ Answer}$$

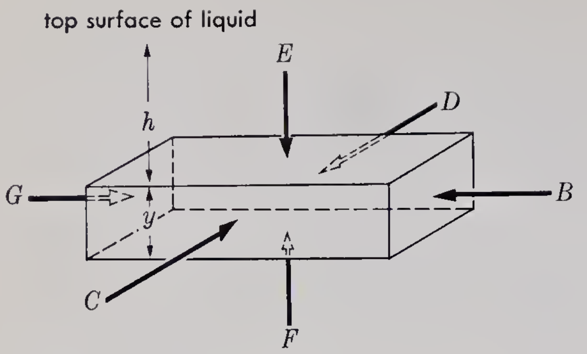


Figure 8–9 This diagram can be used to derive Archimedes' principle.

8–10 Archimedes' principle can be derived from the laws of liquid pressure. Consider the submerged block in Fig. 5–9. It has six surfaces. The forces on these surfaces are not all the same because of differences in depth and area. However, the force (B) on the small end at the right must be equal to the force (G) on the small end at the left, but opposite in direction. Therefore the resultant of G and B is zero. Similarly the resultant of C and D is also zero.

This leaves forces E and F to be considered. Their magnitudes can be calculated from their depth and area. Let A be the area of the top and bottom surfaces of the block, and d_W the weight density of the liquid. Then:

$$\begin{aligned}\text{Pressure on top surface} &= hd_W\\ \text{Force } (E) \text{ on top surface} &= hd_WA\\ \text{Pressure on bottom surface} &= (h+y)d_W\\ \text{Force } (F) \text{ on bottom surface} &= (h+y)d_WA\\ &= hd_WA + yd_WA\end{aligned}$$

Now calculate the buoyant force, $F - E$:

$$\begin{aligned}F - E &= hd_WA + yd_WA - hd_WA\\ &= yd_WA\end{aligned}$$

But y times A is the volume of the block, and also the volume of the displaced liquid. Let V be the volume of the displaced liquid. Then:

$$F - E = d_WV$$

The definition of d_W is:

$$d_W = \frac{\text{weight of an object}}{\text{volume of an object}}$$

For the displaced liquid, therefore,

$$d_W = \frac{\text{weight of displaced liquid}}{V}$$

This can be substituted in the $F - E$ equation:

$$\begin{aligned}F - E &= \frac{\text{weight of displaced liquid}}{V} \times V\\ &= \text{weight of displaced liquid}\end{aligned}$$

$F - E$ is the buoyant force on the block. Therefore the buoyant force on the block is equal to the weight of the displaced liquid. Although this proof was done for a regularly shaped block, it is equally good for an irregular one since you can think of the irregular one as being made of a large number of very small rectangular blocks.

8–11 Flotation is a special case of buoyancy. Archimedes' principle states that an object submerged in a liquid is buoyed up by a force equal to the weight of the liquid displaced. A floating object is partly submerged. Since it remains at the top of the water, it is in equilibrium. The downward force of its weight therefore must be equal to the upward buoyant force. If you put a piece of wood on water, it sinks until it has displaced its own weight in the water and then it stops sinking. If its weight density is half that of water (specific gravity = 0.5), then it sinks until one half of its volume is under water. If its weight density is three quarters that of water (specific gravity = 0.75), then it sinks until three quarters of its volume is under water.

It is customary to refer to the size of a ship as its **displacement**. The carrier Forrestal, for example, has a displacement of almost 60,000 tons. This means that the ship displaces 60,000 tons of sea water. Therefore it weighs 60,000 tons, since it is a floating body. Yet this ship is largely made of materials that have a specific gravity greater than 1. How can it float? The answer lies in its design. The steel of the ship encloses large quantities of air, not only in air-tight compartments, but mostly in rooms and corridors. Therefore if you were to calculate the average specific gravity of the entire volume of the ship, including the air, you would find that it is less than that of water.

Most human beings have a specific gravity slightly less than 1 with their lungs filled with air. For this reason they float in water with most of the body submerged. Lean, muscular people with heavy bone structure may find that they cannot float in fresh water, no matter how hard they try. Evidently their specific gravity is slightly greater than 1. But ocean water has a specific gravity of 1.025. Therefore even a person who normally sinks in fresh water usually floats in salt water. The very salty water of the Great Salt Lake in Utah, U.S.A., has a specific gravity of approximately 1.2. For this reason people are able to float in a most surprising manner there (Fig. 8–10).

Figure 8–10 These girls are floating in the Great Salt Lake in Utah. Since the water in this lake contains a much higher percentage of salt than the water in the ocean, a person cannot sink in it.

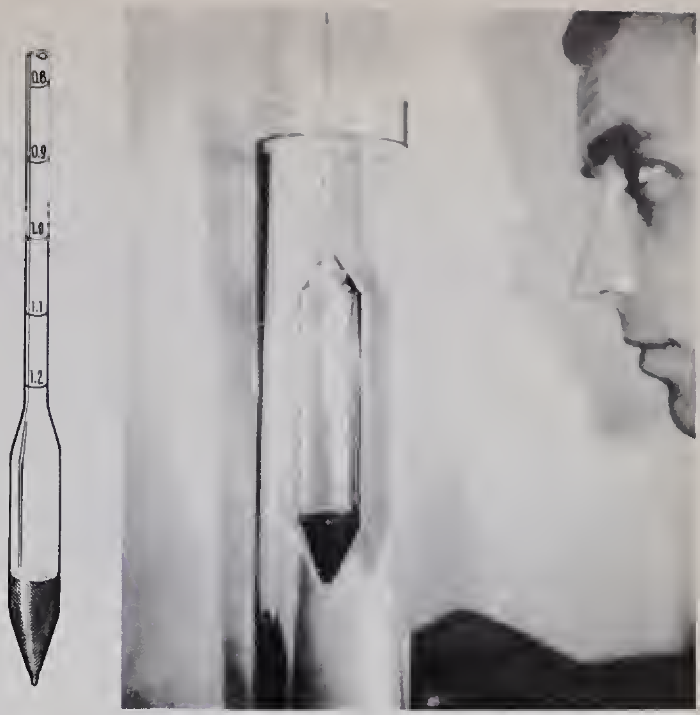


Figure 8–11 Notice in an enlarged section of a hydrometer that the numbers indicating high specific gravity are at the bottom. This is because the hydrometer floats higher in a more dense liquid than in a less dense one.

8–12 Buoyancy has many practical applications. You have seen that objects that float in fresh water float more readily in salt water. On the other hand, they float less readily, or perhaps not at all, in liquids (such as alcohol or gasoline) which are less dense than water. This behavior of floating objects is utilized in the **hydrometer**, illustrated in Fig. 8–11. This instrument consists of a glass tube or bottle weighted at one end so that it floats in an upright position. The upper portion of the tube or the neck of the bottle is marked off with graduations indicating the specific gravity of the liquid in which the hydrometer bulb is floating.

A submarine is designed in such a way that its specific gravity is slightly less than 1 when certain of its tanks are filled with air. However if the air is blown out of these tanks and sea water is let in to take its place, the specific gravity of the craft increases. As a result, the submarine sinks. To raise the submarine, compressed air is used to force the water out of these tanks.

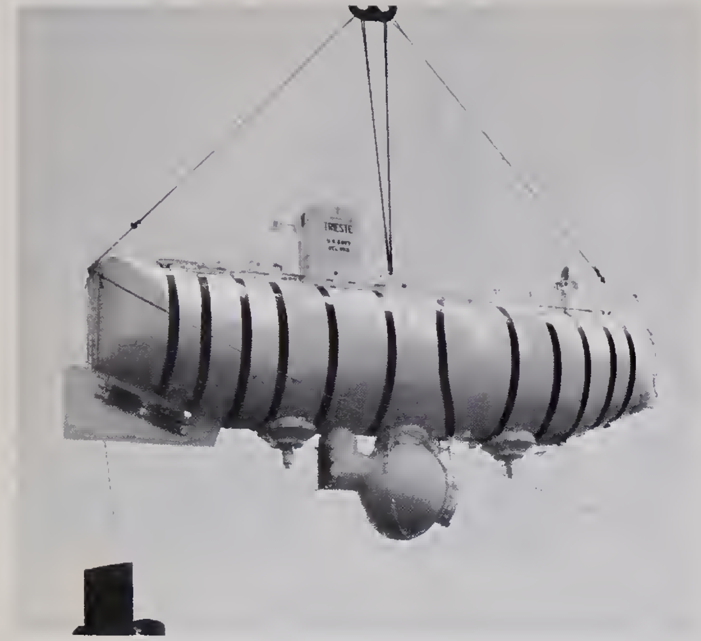


Figure 8–12 The bathyscaphe *Trieste* has been used to explore the depths of the ocean.

The bathyscaphe shown in Fig. 8–12 is used to explore the ocean depths. The observers sit in the small sphere below the large tank which is filled with gasoline. Gasoline has a specific gravity of about 0.68. Therefore there is an upward buoyant force on the tank which acts as a float. About 10 tons of small iron pellets are used as ballast in the float. When the craft is ready to submerge, water is pumped into special tanks to make it heavier. As the bathyscaphe sinks, the increasing pressure forces ocean water into the float tank through holes in the bottom, compressing the gasoline (which is more compressible than water) and keeping the pressure inside the float equal to the pressure outside. Therefore the float does not have to be made as strong as the observation sphere, which must withstand the great pressure of ocean water more than 7 mi deep. A small electric motor allows the operators to move the bathyscaphe along the floor of the ocean. When they wish to rise, they gradually release the iron pellets.

Self Check

1. An object weighs 20 lb in air and 15 lb in water. What is the magnitude of the buoyant force?
2. In what direction is the buoyant force?
3. State the principle you used in answering Questions 1 and 2.
4. Name the man for whom this principle is named.
5. An object has a volume of 40 cm^3. What is its change of weight when submerged in water?
6. Is the loss of weight of the object of Question 5 the same if it is submerged in oil as when it is submerged in water?
7. An object weighs 100 gf and floats in water. Does it displace 100 gf of water, more than 100 gf, or less than 100 gf?
8. The specific gravity of the acid in a car battery is 1.28 when the battery is fully charged. Does a hydrometer float higher or lower in this acid than in water?
9. The specific gravity of ice is 0.92. What percent of the volume of a floating ice cube is above water?
10. Describe two practical applications of buoyancy.

Problems

Ⓐ **1.** A piece of metal weighs 500 gf in air and 400 gf in water. What is the volume of the metal?

2. What is the weight density of the metal in Problem 1? Its mass density? Its specific gravity?

3. A stone has a specific gravity of 3.00. It weighs 600 gf in air. What is its volume? What will it weigh in water?

4. A 500-lb stone has a volume of 3.00 ft^3. What will it weigh in water?

5. A piece of metal with a volume of 50 cm^3 weighs 300 gf. If it is immersed in oil with a specific gravity of 0.80, what volume of oil does it displace? What weight of oil does it displace? What is the apparent weight of the metal?

6. What is the volume of a 180-lb man who barely floats in fresh water?

7. A floating block of wood weighs 20 kgf. How many cubic centimeters of fresh water does it displace? If the block is a cube 30 cm on a side, how far will it sink in fresh water?

8. Find the specific gravity of the block of wood of Problem 7, and show that it is equal to the ratio of the depth of the block below water to the height of the block.

B **9.** A boy can lift a weight of 100 lb. What is the weight in air of a stone he can just lift in water if the specific gravity of the stone is 3.0?

Discussion Questions

1. A submarine cruises at a constant depth of 100 ft below the surface of the water. What is its specific gravity?
2. Pumice is a volcanic rock that floats. It is made of exactly the same materials as many volcanic rocks that do not float. Why can it float?

Gases Exert Pressure

Most of the discussion in this part of the chapter is concerned with the behavior of air, because it is the most abundant and most important gas. However, the laws governing its behavior are also true for other gases.

8–13 The weight of air causes air pressure. You have learned that the pressure exerted by the water in a lake or ocean is due to the weight of the water (Fig. 8–2). A similar situation exists in the atmosphere, the "ocean of air" at the bottom of which we live.

The casual observer does not notice air pressure, nor does he notice any evidence that air has weight, since air has a very low weight density compared to most substances. In fact, a cubic foot of the air around you weighs only about 1⅓ oz. The air under a card table weighs about 1 lb. If you weigh a basketball when it is at proper playing pressure and again when some of the air has been let out, you will find a difference in weight.

The pressure of the atmosphere is quite large, about 14.7 lb/in^2 at sea level. This means that the force on a single square foot is well over a ton. The reason you seldom notice air pressure is that it exists inside your bodies as well as out. The force pushing in equals the force pushing out.

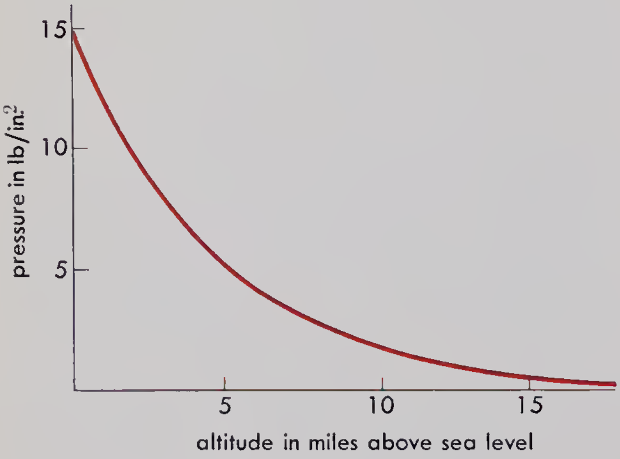
Do It Now

1. Get a gallon can with a small opening that can be closed with a rubber stopper. Be sure to rinse the can out thoroughly so that any flammable material it might have contained is completely gone. Duplicating fluid used in the school office comes in such a can. If you have a good vacuum pump, use it to pump air out of the can and note the effect of air pressure. If you do not have a vacuum pump, put about ¼ inch of water in the bottom of the can and boil it to drive out the air. Then stopper the can tightly and cool it to condense the steam, reducing the pressure inside.
2. Measure the dimensions of a similar can and calculate the total force due to air pressure of 14.7 lb/in^2.

8–14 Air pressure varies with altitude. In your study of liquid pressure you found that pressure increases with increasing depth. This is to be expected, of course, since at greater depths there is more liquid pushing down from above. Similarly, in the "ocean of air" the air pressure is greatest at the bottom, which is the surface of the earth. You notice this when you rise in a fast elevator. The air pressure on the outside of your eardrum decreases, but the pressure inside your body does not change as rapidly; the resulting pressure difference causes your eardrum to bulge outward. Swallowing helps adjust the pressure because there is an air passage between the ear and the mouth. On the trip down, the reverse situation causes your eardrum to bulge inward.

The graph in Fig. 8–13 shows how air pressure changes with altitude. In a liquid, as you have learned, the pressure is proportional to depth. For every 1-ft change in depth of water, for example, the pressure changes 0.43 lb/in^2. As you rise through the atmosphere, however, the pressure decreases most rapidly in the first few miles. The difference between liquids and air in this respect is related to their compressibility. It is all but impossible to compress a liquid. Therefore the density of a liquid is a constant (unless the temperature changes) and each additional unit of depth contributes the same share of additional pressure. On the other hand, air is easily compressed. As a result the air near the earth's surface is compressed by the weight of the air above it and is more dense than that at higher altitudes. Consequently, the pressure contributed by 100 ft of air near the surface of the earth is greater than that contributed by 100 ft of air high in the atmosphere.

Figure 8–13 This graph shows the variation of atmospheric pressure with elevation.



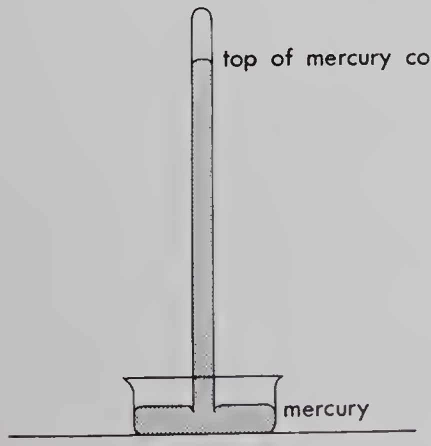
8–15 Air pressure exerts force that is equal in all directions. In your study of pressure in liquids you found that the force due to pressure at a point is exerted equally in all directions. Precisely the same situation holds true in gases. Were it not for this fact, plants, animals, and dwellings would all be crushed by the tremendous weight of the atmosphere. But atmospheric pressure exerts force upward on the bottom surface of a tree leaf as well as downward on the top surface. It is because these opposing forces are so nearly balanced that you seldom notice the forces due to atmospheric pressure. The pressure at the center of a tornado is extremely low. When such a storm passes over a house, the house may literally explode because of the greater pressure inside. Chickens in the path of such a storm have been plucked clean as the air inside each quill explodes the feather.

8–16 Archimedes' principle applies to gases. According to Archimedes' principle, an object immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced. The word "fluid" is in the statement because the principle applies to gases as well as to liquids. A fluid — a substance that flows — may be either a gas or a liquid. The proof of Archimedes' principle (p. 199) was based on the assumption that the object was immersed in a liquid. With a slight change to account for the fact that the density of a gas increases with depth, however, the same proof can also be used for gases.

The buoyant force on an object immersed in air is equal to the weight of the air displaced. The most familiar application of the buoyant force of air is in lighter-than-air craft such as airships and balloons. Hydrogen, the gas of lowest density, was long used in these lighter-than-air craft. This use has been almost entirely dropped for helium. Helium is more expensive, but it is nonexplosive. The weight density of helium is almost twice that of hydrogen. In spite of this the lifting power of a helium-filled craft may be more than 90 percent of that of a hydrogen-filled one. For an understanding of this paradox, see the problems on p. 207.

8–17 The mercury barometer measures air pressure. When you listen to a weather report, you may hear, "Barometer reads 29.8 and rising." This is a report of the current air pressure. The most accurate kind of barometer for measuring air pressure is illustrated in Fig. 8–14. To make it, a long glass tube, sealed at one end, is completely filled with mercury and then inverted in a cup of mercury. If the tube is more than 30 in long, the mercury column will drop to about 30 in, leaving an almost perfect vacuum above it. The air pressure on the mercury in the cup is exactly equal to the mercury pressure inside the tube at a point that is level with the mercury in the cup. As the air pressure changes, the level of the mercury in the tube changes. It is more convenient to measure this in inches or millimeters of mercury than to convert it to pounds per square inch or dynes per square centimeter. Normal atmospheric pressure is defined as 760 mm of mercury, which is approximately equal to 30 in (actually 29.92 in). It is the average atmospheric pressure at sea level. Study the problem on pressure in Example 5 below.

Figure 8–14 A mercury barometer is made by filling a glass tube with mercury and inverting it into a cup of mercury. The top of the mercury column drops to about 30 inches above the level in the cup. The height of the mercury in the tube above the level in the cup is a measure of air pressure.



EXAMPLE 5

Find the pressure in pounds per square inch due to a column of mercury 30.0 in high. Mercury has a specific gravity of 13.6.

Given: $h = 30.0 \text{ in} = 2.50 \text{ ft}$
sp. gr. of mercury = 13.6

To find: P

Solution: d_W of mercury = specific gravity of mercury times d_W of water

$$d_W \text{ (mercury)} = 13.6 \times 62.4 \text{ lb/ft}^3$$

$$P = hd_W$$

$$= 2.50 \text{ ft} \times 13.6 \times 62.4 \frac{\text{lb}}{\text{ft}^3}$$

$$= 2.12 \times 10^3 \frac{\text{lb}}{\text{ft}^2}$$

$$= \frac{2.12 \times 10^3 \text{ lb}}{\text{ft}^2} \times \frac{1 \text{ ft}^2}{144 \text{ in}^2} = 14.7 \frac{\text{lb}}{\text{in}^2},$$

Answer

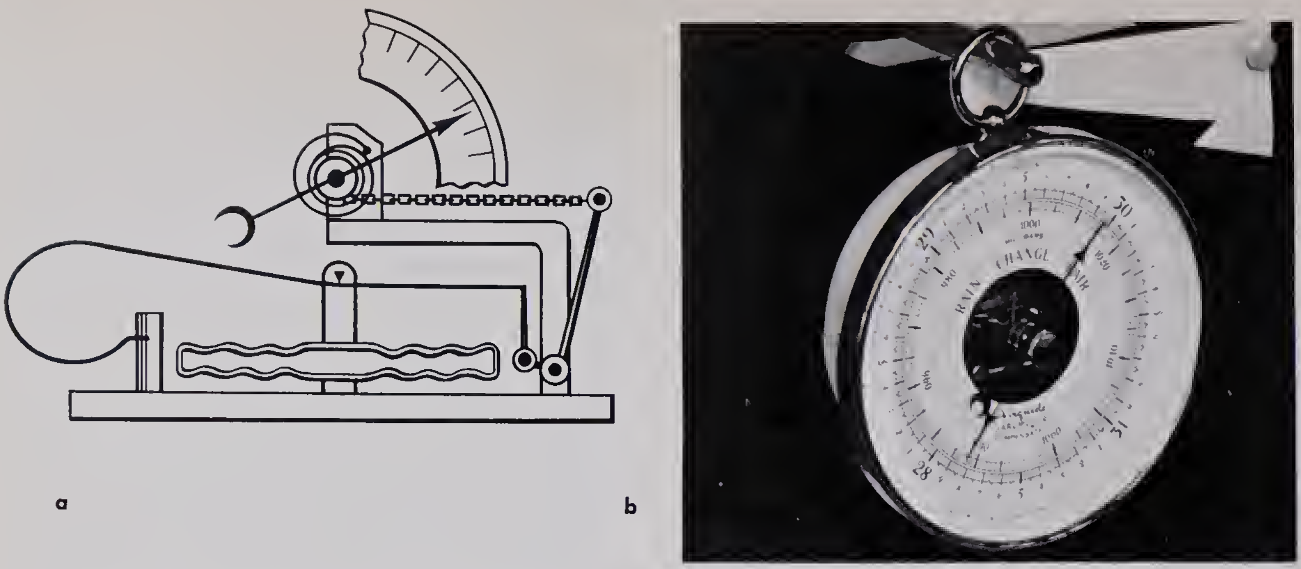


Figure 8–15 a. The pressure-sensitive portion of the aneroid barometer is the hollow disk from which the air has been removed. The hollow disks, which are very thin and flexible, are prevented from collapsing by the spring. An increase in air pressure squeezes the disk a little, and a decrease in air pressure permits it to expand somewhat. This slight change in thickness of the disk is a reliable indication of air pressure. **b.** An aneroid barometer.

You may sometimes, especially on weather maps, find pressure given in bars or millibars.

$$\begin{aligned} 1 \text{ bar} &= 10^6 \text{ dyne/cm}^2 \\ &= 10 \text{ N/cm}^2 \\ 1 \text{ millibar} &= 10^3 \text{ dyne/cm}^2 \\ &= 10^{-2} \text{ N/cm}^2 \end{aligned}$$

A pressure of 1 bar is 14.5 lb/in^2, almost the same as normal atmospheric pressure.

The mercury barometer is the standard instrument for measuring atmospheric pressure. To obtain accurate readings, the barometer must be absolutely vertical and, of course, not jiggling. In addition, heat causes mercury to expand and its specific gravity becomes correspondingly lower. Therefore the readings must be corrected for temperature in order to be accurate.

8–18 An aneroid barometer is very convenient. Although the mercury barometer is extremely reliable and is simple to construct, it has the disadvantage of being bulky and fragile. A useful substitute is the **aneroid** barometer. Aneroid, derived from Greek, means "without liquid." A diagram of this barometer is shown in Fig. 8–15a. The scale of an aneroid barometer is commonly calibrated in inches and millimeters of mercury, as shown in Fig. 8–15b. Since the barometer is often used to help predict weather, it is frequently marked in terms of possible future weather, as in this case.

An aneroid barometer is more sturdy and more portable than the mercury barometer. It can be constructed so that a very small pressure change produces a noticeable change in the position of the pointer. Accordingly it can be used as an *altimeter* in an airplane. As the plane rises, the altimeter needle goes down because of the reduced pressure. The numbers on the dial read feet of height rather than inches of mercury. Before an airplane takes off, the altimeter is adjusted to take into account the barometric pressure at the field; then the altimeter shows the altitude of the field above sea level. Because the barometric pressure changes from place to place and from time to time, the pilot periodically adjusts the altimeter in accordance with instructions radioed to him.

8–19 Gas pressure is widely used. Gases under pressure are used for many purposes: to operate pumps, to keep water out of underwater tunnels while they are being built, to operate drills that rip up pavement, to supply gas for homes. You can probably think of other uses.

Self Check

1. What is the cause of atmospheric pressure?
2. What is normal atmospheric pressure in pounds per square inch, in inches of mercury, and in millimeters of mercury?
3. Why don't our bodies collapse under the great force due to air pressure?
4. Compare the change in air pressure as you rise in the atmosphere with the change in water pressure as you go down in a lake or ocean.
5. Why does a helium-filled balloon rise?
6. Describe the construction of a mercury barometer.

Problems

Ⓐ 1. A balloon weighing 100 lb is filled with 10,000 ft^3 of hydrogen. If the density of air at 32°F is 0.0807 lb/ft^3 and that of hydrogen is 0.00561 lb/ft^3, find the net upward force on the balloon.

2. If the same balloon is filled with helium (density 0.0114 lb/ft^3), what is the net upward force?

3. If a tire gauge reads 28.0 lb/in^2 pressure, what is the absolute pressure?

Discussion Questions

1. Mountain climbers in the Himalayas wear oxygen masks. Why is this necessary?
2. A diving bell is a large bell-shaped object that is open at the bottom. It is lowered into deep water with men inside it so that they can work on the bottom of the water. As the pressure goes up, so does the air pressure inside the bell, supplied by hoses from above. Thus no water gets into the bell. As the pressure increases around them, it forces more air to dissolve in the blood of the men than when the pressure was lower. If the men came up to the top of the water suddenly, what might happen that would be very dangerous? First try to guess, and then look up the "bends," the disease that afflicts them.
3. Which weighs more, a pound of lead or a pound of feathers? This is a riddle often asked to trick you. They should weigh the same, of course. But consider the problem of buoyancy due to the fact that you weigh them in air. Suppose that you have a true pound mass of each, and that you put them in opposite pans of an equal-arm balance. Will they balance, or will one seem to weigh more than the other?
4. An engineer measuring the pressure in a tank may say that it has 10 in of vacuum. What does he mean?

Motion Affects Pressure

8–20 Pressure is reduced inside a moving fluid. Can you pitch a "curve ball"? For years people have been convinced that certain pitchers could pitch a ball that curves to the right or left. A few years ago some skeptics doubted this. They said that the only curve a ball can take, once it leaves the pitcher's hand, is the parabola determined by the laws of projectiles. Some enterprising scientists took pictures of a ball in flight, pitched by a man who said he could make it curve. The results showed a

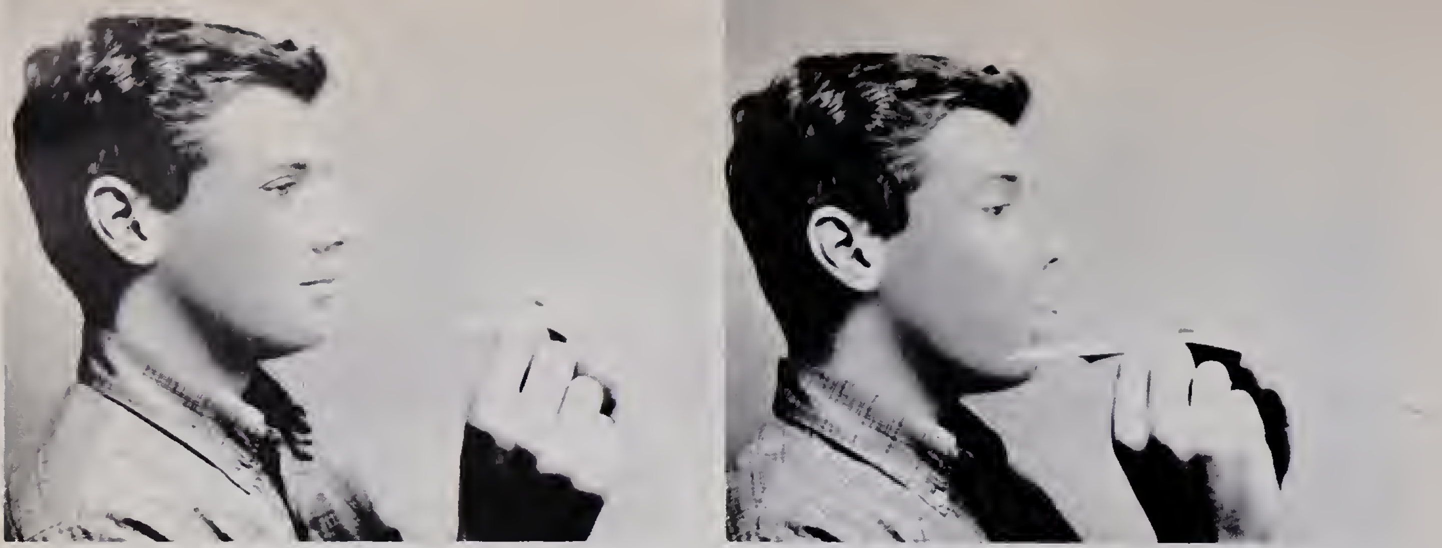


Figure 8–16 When you are not blowing on it, the paper looks like the photo on the left. When you blow, the free end rises as shown on the right.

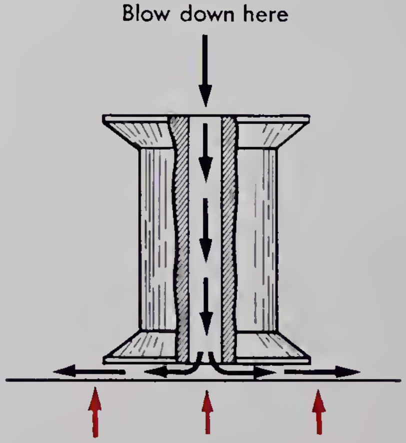
change in the ball's direction. Obviously the ball's path is curved in a manner not completely explained by the projectile laws.

To understand how this can happen, you need to know a law that was developed by Daniel Bernoulli, a Swiss scientist of the 18th century. According to Bernoulli's principle, the pressure in a moving fluid is less when the velocity is high, and greater when the velocity is low. You can show very simply that this law is true. Hold a sheet of paper as shown in Fig. 8–16, and blow across the top. The loose end of the paper rises because the pressure of the quiet air below it is greater than the pressure of the moving air above it. Figure 8–17 shows another simple experiment that demonstrates Bernoulli's principle.

If you try to stand up when a strong wind is blowing, you may decide that Bernoulli's principle is all wrong. Here is a fast-moving fluid, but instead of exerting a reduced pressure, it seems to be exerting an increased pressure on you. This is because you are standing still and trying to stop the wind. You are contending with the forces of Newton's laws. You exert a decelerating ($F = ma$) force on the moving air and in return it exerts an equal and opposite force upon you (Newton's third law). If you could suddenly make yourself as light as a leaf and let yourself be carried by the stream of air, you would no longer feel that the wind was exerting a large force on you. It is the pressure inside the stream of air itself that is reduced when the speed increases. The pressure difference results in a force perpendicular to the boundary between fast-moving and slow-moving or quiet air.

Just what has this to do with the curving path of a baseball? A ball will not curve unless it is spinning. In Fig. 8–18 you see a diagram of a ball spinning counterclockwise as it moves through the air. From the point of view of the ball, the air is moving as shown by the arrows. The spinning ball

Figure 8–17 Put a pin through a light card. Then put the end of the pin up the hole of a large spool. When you blow down the hole, the card will not fall because the moving air between the bottom of the spool and the top of the card exerts reduced pressure on the card.



Force due to air pressure is greater here than where air is moving, and so holds up card.

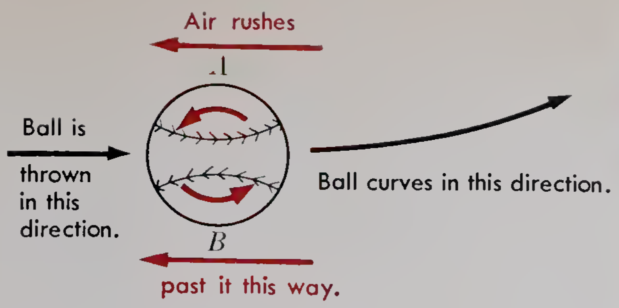

Air rushes
A
Ball is thrown in this direction.
Ball curves in this direction.
B
past it this way.

Figure 8–18 A spinning ball curves because the air at A, helped by the spin, rushes past the ball faster than the air at B, which is slowed by the spin of the ball. For this reason there is more pressure at B than at A.

carries a little air around with it, thus giving the air on one side a little added velocity and slowing down the air on the other side. Since the pressure is greater where the air velocity is less, the pressure difference causes a force that gives the ball a curve to one side. Roughening the surface of the ball gives it a chance to pick up more air as it spins, increasing the curvature of the path.

8–21 Bernoulli's principle has many applications. The next time you have the chance, look at the wing of an airplane. You will see that it is curved like the piece of paper in Fig. 8–16. As the plane moves along the runway, the air rushes over its long upper wing surface more rapidly than over the shorter lower surface, and the pressure difference causes the plane to rise. If the "angle of attack" of the wing is varied, the lift varies considerably.

The action of an atomizer or spray gun is also dependent on Bernoulli's principle. A swift stream of air is forced over the top of the vertical tube. As a result the air pressure at the top of the tube is less than the air pressure at the surface of the liquid in the container. The unbalanced pressure causes a force that sends liquid up the tube. As the liquid starts to spill over the top, the air stream blows it into many tiny drops that spray out of the nozzle.

Do It Now

Hold two sheets of paper by the upper edges so that they hang vertically about 4 in apart. Blow between them and explain the result.

Self Check

1. State Bernoulli's principle.
2. Tell how Bernoulli's principle is involved in the operation of one important device.

Discussion Questions

1. How is Bernoulli's principle applied in the carburetor of an automobile?
2. How does Bernoulli's principle help a sailboat to sail into the wind?

Chapter Summary

The specific gravity of a substance compares its density with that of water. Mass density is mass per unit volume of a substance and is not affected by gravitation. Weight density is weight per unit volume and varies with changes in gravitational forces.

Pressure is force per unit area. In a liquid, pressure increases with depth, and the increase is proportional to the change in depth and to the weight density of the liquid. Water supply systems make use of liquid pressure. Within a liquid the force due to pressure is exerted equally in all directions. If pressure is exerted on a confined liquid, the pressure is transmitted, without loss, throughout the liquid. This fact makes possible the construction of the hydraulic press. The ideal mechanical advantage of a hydraulic press is the ratio of the piston areas in the two cylinders.

An object either partly or totally immersed in a fluid appears to have a smaller weight than when it is not so immersed. The apparent loss of weight is called the buoyant force and is equal to the weight of the fluid displaced. A floating object displaces its own weight in a liquid. An object floats in water if its specific gravity is less than 1 and sinks if its specific gravity is greater than 1.

Air exerts pressure because of its weight. The pressure decreases with increase in altitude, but because air is compressible, the pressure changes most rapidly near the surface of the earth where the air is most dense. As with liquids, the force due to air pressure is exerted equally in all directions, and gases, as well as liquids, exhibit buoyancy. Air pressure is measured by mercury and aneroid barometers and by other devices.

Pressure in a moving fluid is decreased as velocity increases. Many important practical applications are made of this principle, including airplane lift and spray guns.

Vocabulary

specific gravity (*p. 189*)
mass density (*p. 190*)
weight density (*p. 191*)
pressure (*p. 191*)
absolute pressure (*p. 192*)
gauge pressure (*p. 192*)
Pascal's principle (*p. 196*)
hydrostatic paradox (*p. 196*)
hydraulic press (*p. 196*)
buoyancy, buoyant force (*p. 198*)
Archimedes' principle (*p. 199*)
fluid (*p. 199*)
displacement (*p. 200*)
hydrometer (*p. 201*)
bathyscaphe (*p. 202*)
atmospheric pressure (*p. 203*)
mercury barometer (*p. 205*)
bar, millibar (*p. 206*)
aneroid barometer (*p. 206*)
altimeter (*p. 206*)
Bernoulli's principle (*p. 208*)

Problems

Ⓐ **1.** What is the pressure in lb/in^2 on the road beneath a car weighing 2500 lb if the area of contact of each tire with the road is 50 in^2?

2. What is the pressure in dyne/cm^2 at a depth of 1000 m in fresh water?

3. The bathyscaphe *Trieste* once dove to a depth of 35,800 ft in the Pacific Ocean. Assuming that the density of sea water remains constant at 64.0 lb/ft^3 throughout the whole distance, calculate the pressure.

4. The observers in the *Trieste* sat in a spherical gondola 6.5 ft in diameter. What was the total force on the gondola? (Area of the surface of a sphere is $4\pi r^2$.)

5. What is the force on the vertical walls of a cylindrical water tank 2.0 m in diameter if the water is 3.0 m deep?

6. A hole in a barrel is plugged with a cork that can stand a pressure of 3.0 lb/in^2 before being pushed out. The hole is 1.0 ft above the bottom of the barrel. What height of water can be put in the barrel?

7. A hydraulic press has pistons with areas of 4.0 cm^2 and 640.0 cm^2. What force on the smaller piston is necessary to lift a load of 10,000 kgf?

8. The area of the small and large pistons of a hydraulic press are 2.0 in^2 and 100.0 in^2 respectively. What load can be supported by a force of 100.0 lb applied to the small piston?

9. Gold has a density of 19.3 gf/cm^3. If a king's crown weighed 4000 gf in air and 3750 gf in water, was it pure gold?

10. A stone weighs 200 lb in air and has a specific gravity of 2.5. What is its apparent weight in fresh water?

11. A metal cylinder weighs 250 gf in air, 210 gf in water, and 215 gf in oil. (a) What is the volume of the cylinder? (b) What is its density? (c) What volume of oil does it displace? (d) What weight of oil does it displace? (e) What is the density of the oil?

12. A flat board is floating on a pond. If the board is 30 cm long and 10 cm wide, and floats with 1.0 cm out of water, how much of the board will still be out of water if a 200-gf frog jumps onto the board?

13. A barometer reads 60 cm of mercury when up in a balloon. What is gauge pressure at that altitude?

Ⓑ **14.** The force due to pressure in a liquid is always perpendicular to the surfaces of the container. Keeping this in mind, calculate the total force on the sloping bottom of a water-filled tank. The top of the tank is 100 cm long and 30 cm wide, and it is 10 cm deep at one of the narrow ends and 50 cm deep at the other narrow end.

15. The bathyscaphe *Trieste* holds approximately 3500 ft^3 of gasoline in its float. If the density of the gasoline is 42 lb/ft^3 and that of sea water is 64 lb/ft^3, what is the buoyant force due to the gasoline?

Discussion Questions

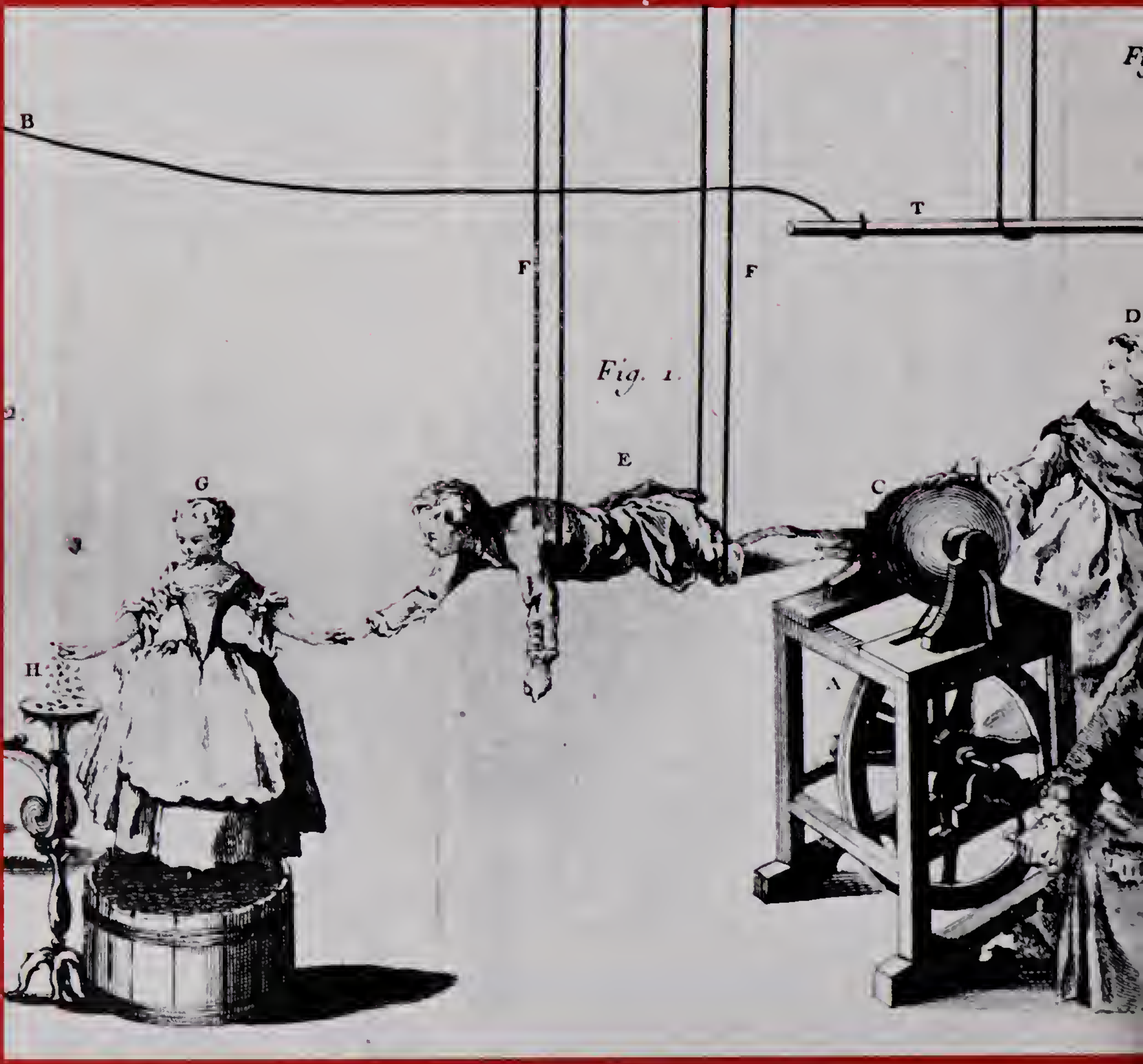
1. Why can a man travel on the top of snow with skis or snowshoes when he would sink into it without them?
2. Why does a sharp knife cut better than a dull one?
3. Eggshells are somewhat porous, allowing water vapor and gases in and out. Consequently when eggs are kept in storage they tend to dry up slightly. How can you tell the difference between a fresh egg and one that is not fresh, without cracking the shell or smelling it?
4. Red blood cells carry oxygen. Indians in the high Andes Mountains of South America have more red blood cells per cm^3 of blood than do people who live at lower elevations. Why is this a help to them?
5. Two rigid balloons having the same volume and weight are filled with helium. One has a valve that lets gas out of the balloon whenever the pressure inside is greater than that outside. If the two balloons are released together, which will rise higher? Why?
6. Two balloons having the same volume and weight are filled with helium at atmospheric pressure. One is rigid, without a valve. The other also has no valve, but is free to expand as the pressure outside decreases. If they are released together, which will rise higher? Why?
7. A chemist uses brass weights for careful weighing. Will buoyancy cause more error when he weighs balsa wood or when he weighs iron shot? Why?
8. Usually when you are taking a shower, the curtain, if of a light-weight material, will shift toward you. Why?

Work on Your Own

1. Calculate the pressure exerted by a girl in high heels when she has all of her weight on the heel of one foot. This involves your devising some method for measuring the area of the heel. Compare the pressure you find with the pressure exerted when she stands on one bare foot. A similar experiment could be done to find the pressure exerted by an ice skater. You might also try finding the pressure exerted by the blade of a knife when you exert a force of 1 lb on the handle. A micrometer might help you to find the area of the cutting edge.
2. Examine battery testers and antifreeze testers in a garage and observe how they work and how they are marked. You may not find the specific gravity marked on the instrument.
3. Oil is less dense than water and more dense than alcohol. By mixing water and alcohol in the proper proportion you can produce a solution that has the same density as the oil. A drop of oil squeezed into this solution from a medicine dropper with its opening below the surface will remain at the same level. Your problem is to manipulate the density of the solution so that this happens.
4. The following liquids have different densities: mercury, carbon tetrachloride, water, gasoline. Pour a little of each in the order listed above into a tall, narrow glass cylinder. Compare their densities from what you observe. Then drop into the cylinder small bits of iron, copper, colored glass, balsa wood, other kinds of wood, a hard plastic, and ice. Explain what happens.
5. Weigh a beaker of water on a laboratory balance. Predict what will happen if you stick your finger in the water without touching the side or bottom of the beaker. Check your prediction.
6. The density of air at sea level when the temperature is 75°F is about 0.0074 lb/ft^3. Check the statement made on p. 191 that the air under a card table weighs about a pound by measuring a card table and calculating the weight. Measure the size of your classroom and calculate the weight of the air. Try with other volumes.

UNIT THREE

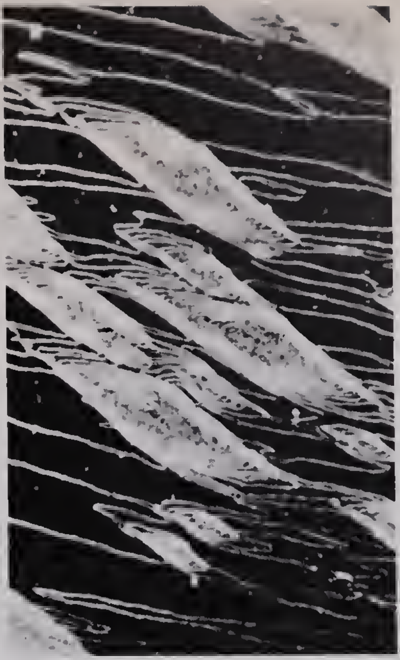
Electricity and Magnetism

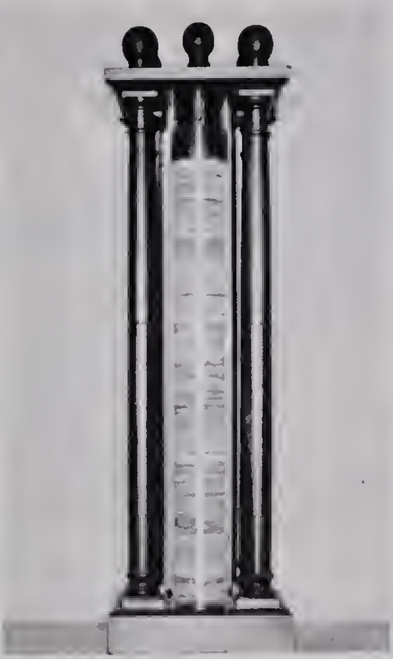


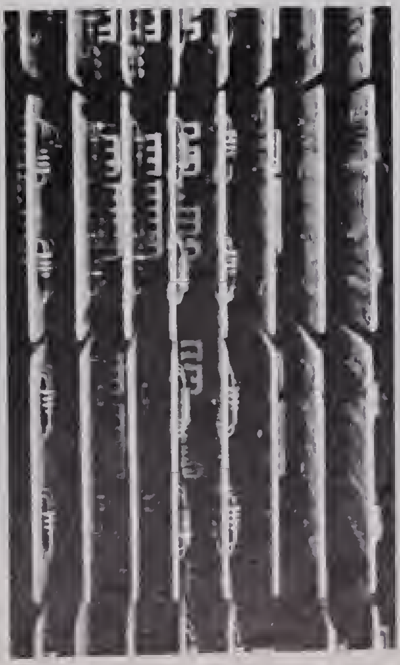
Burndy Libra

In this 18th century electrostatic demonstration, when the friction generator was turned, the boy and the girl became electrically charged, and bits of paper were attracted by the girl.

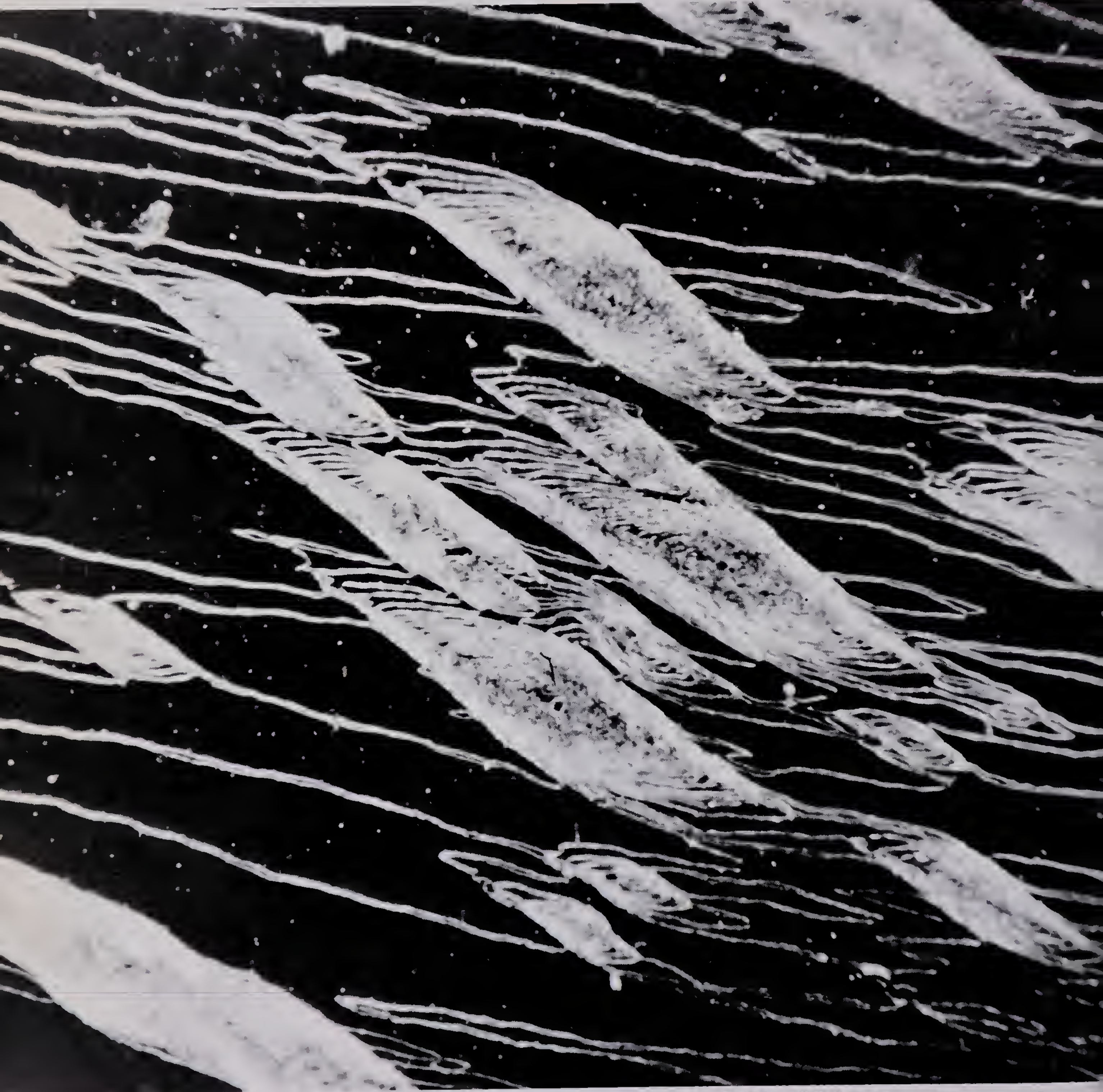
Most of man's understanding of the nature of magnetism and electricity has been developed since about the year 1800. In that time, however, these understandings have become some of the most fundamental and useful concepts in all of physics. Less than one hundred and fifty years ago scientists were quite convinced that magnetism and electricity were completely unrelated; there was no evidence to the contrary. Then came the breakthrough, and in a few years the foundations of modern electrical science were developed. Today scientists know that magnetism and electricity are intimately related, that every changing magnetic field produces an electric field, and that every moving charged particle produces a magnetic field. In this unit you will not only learn something of what scientists know today about magnetic and electrical phenomena, but you will also learn how they developed these concepts.







CHAPTER 9



Courtesy of Bell Telephone Laboratories, Inc.

Magnetic domains in a nickel-iron alloy.

Magnetism and Electromagnetism

Only within the past 150 years have scientists studied the relationship between electricity and magnetism. An understanding of this relationship has led to the construction of electromagnets, motors and generators, telegraph and telephone systems, and many other devices.

While some scientists have been developing these useful applications of electromagnetism, others have been turning their attention to magnetic phenomena within and around the earth. They have learned that the earth's magnetic field is probably caused by currents of fluid matter within the earth; and some may be caused by currents of charged particles in the atmosphere.

Scientists have studied the behavior of bar magnets and electromagnets and have developed theories to account for the observations. One of the techniques for studying the details of magnetism is illustrated in the photomicrograph at the left. Here a thin film of nickel-iron alloy has been magnetized. Its magnetic anatomy has been made visible by spreading magnetic powder over the alloy.

Magnetic Behavior

9–1 Materials vary in degree of magnetism. Sometimes a machinist uses a magnetized screwdriver to hold a small screw in place while starting to drive it in. If he uses the screwdriver on a brass screw, however, he finds that it will not hold the screw. You probably have experimented with magnets and know that the common materials affected by magnetism contain some form of the element iron. Steel nuts and bolts, pieces of scrap iron, paper clips, and baling wire are magnetic.

Most chemical compounds of iron are almost completely nonmagnetic. The iron in blood and the iron in certain foods and medicines are in chemical combination with other elements and are therefore nonmagnetic. However, one important compound of iron and oxygen is distinctly magnetic. This abundant form of iron ore is known as magnetite (Fe_3O_4). Geophysical prospectors use magnetic measuring instruments to reveal the presence of magnetite and other magnetic, iron-containing minerals.

Although iron is the most common magnetic substance, it is not the only one. The elements nickel and cobalt are also mag-

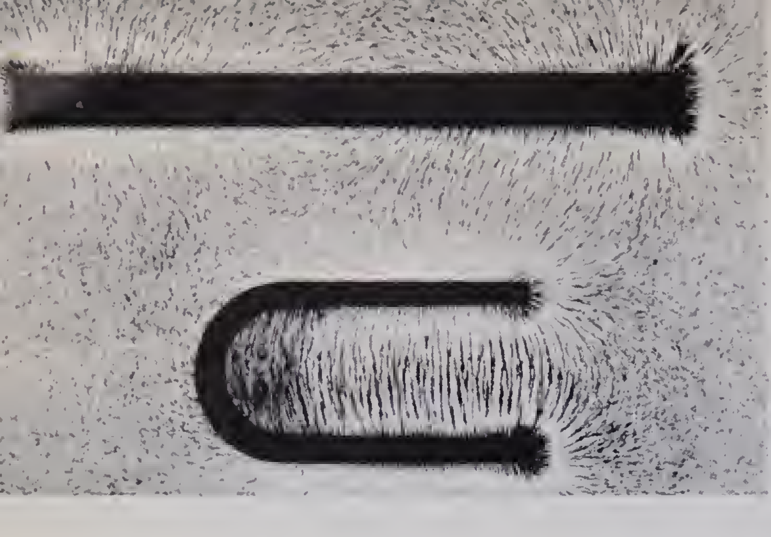


Figure 9–1 In this photograph iron filings were scattered on a sheet of glass above a bar magnet and a horseshoe magnet (a bar magnet bent into this shape). The arrangement of the filings indicates the general nature of the magnetic region around the magnets. In each magnet the magnetism seems to be concentrated in two regions, or poles, near the ends.

netic. (A United States five-cent piece or "nickel" shows little or no magnetic properties, because "nickel" coin-metal is an alloy of 25% nickel and 75% copper. Canadian five-cent pieces, on the other hand, are nearly pure nickel, and show definite magnetic properties.)

Indeed, all materials show some magnetic effect, although it is usually so minute that special instruments are required to detect it. Some substances are even repelled by a magnet, but the repelling force is very slight.

Three terms are used to describe magnetic properties:

1. *Ferromagnetic* — materials which are strongly attracted by a magnet. Examples: iron, nickel, cobalt.
2. *Paramagnetic* — all materials, including ferromagnetic ones, which are attracted by a magnet. Examples of weak paramagnetic materials: oxygen, aluminum, platinum.
3. *Diamagnetic* — materials which are repelled by a magnet. Example: bismuth.

9–2 Magnets have poles. If you put a magnet into a box of tacks, you find that it picks up many tacks at each of its ends and very few at its middle. The regions of strongest magnetism near the ends are called the **poles** of the magnet, or the **magnetic poles.** Most magnets have two such poles. The poles can be found also by an experiment like that in Fig. 9–1.

Centuries ago men discovered that if they put a magnetized needle on a straw floating in water, it would swing until it pointed approximately north and south. They named the end that pointed north the **north-seeking pole** of the magnet or, more simply, the **north pole (N-pole).** The other end was called the **south-seeking pole**, or the **south pole (S-pole).** Such a suspended needle was often used as a compass on ships.

In Fig. 9–1 you see that the lines of iron filings do not lead to a single spot at each end of the magnet. A magnetic pole is not a *pinpoint;* it is a *region.* This becomes even more obvious if you break a magnet in two, as shown in Fig. 9–2. Each magnet formed has two poles. Any theory developed about magnetism must account for the appearance of new poles when a magnet is broken.

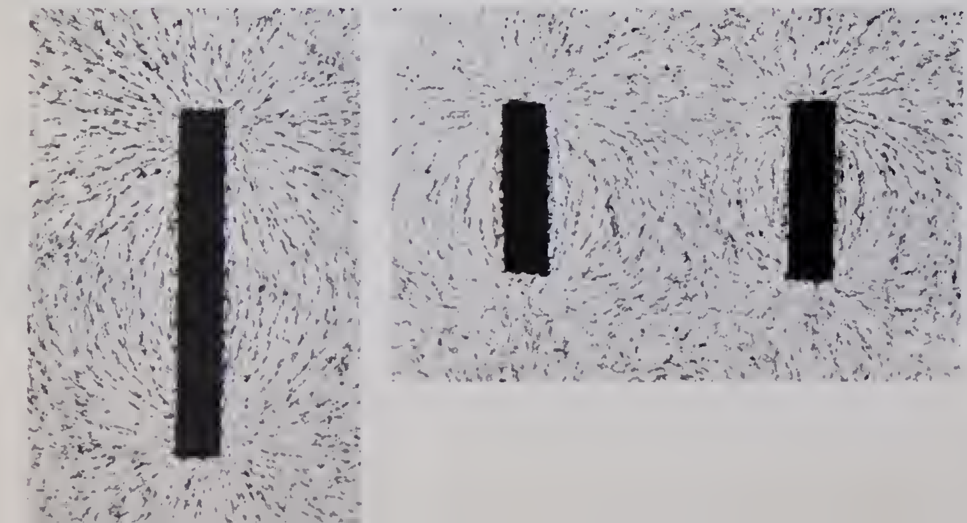


Figure 9–2 The effects of breaking a magnet. Before being broken, the bar magnet seemed to have little magnetism near its center. After it is broken, however, it shows a new pole near each of the two new ends. This indicates that the magnetism of a bar magnet exists all through it, not just at the ends.

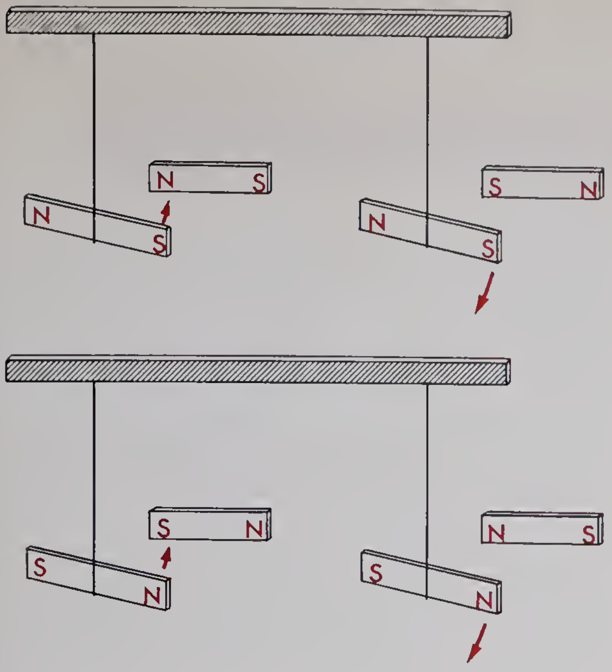


Figure 9–3 This experiment with two magnets, one suspended and one held in the hand, shows that unlike poles attract each other and like poles repel each other.

9–3 The law of magnets describes their behavior. The experiment shown in Fig. 9–3 illustrates the **law of magnets**: Like magnetic poles repel each other; unlike poles attract each other. The law of magnets is very much like the law describing the behavior of positive and negative electric charges. Coulomb, who studied the forces between static electric charges (p. 85), also studied the forces between magnets. He found that the force between two magnetic poles varies directly as the product of the strength of the poles and inversely as the square of the distance between them; that is,

$$F = \frac{km_1m_2}{s^2}$$

where m_1 and m_2 are the strengths of the magnetic poles and s is the distance between them. This law is very much like the one for static charges. It differs from it, however, in being only an approximate law since the law of magnets assumes that magnetic poles are points, which they are not.

Because the rules of behavior for magnets are similar to those for charges, you may be tempted to think of electricity and magnetism as two aspects of the same thing. This is not the case, as pointed up by the observation that a positive charge can exist all by itself, but a north pole cannot. Magnetic poles always occur in pairs, one north and one south.

9–4 Permanent magnets can be made. You can make a magnet easily out of a needle or a nail by stroking it, in one direction only, with the pole of another magnet. When compasses were used first, the only permanent magnets were pieces of a naturally magnetized substance called *lodestone* (the mineral magnetite). Every time a ship's captain wanted to use his compass, he had to magnetize the needle by stroking it with a piece of lodestone. The needle was made of soft iron, the only kind of iron then known. Soft iron does not hold its magnetism. Now permanent magnets that remain magnetized for a very long time can be made by stroking a good steel needle or nail with a magnet. This method for making permanent magnets involves bringing a suitable ferromagnetic material under the influence of a magnet.

Permanent magnets can be weakened by vibrating them severely, by heating them up to several hundred degrees Celsius, or by using a special electric device to reduce the magnetism to zero. Electric demagnetizing devices are used to repair watches which have become magnetized.

Do It Now

Try to magnetize sewing needles, nails, iron bolts, and pieces of spring steel by rubbing them many times, in one direction only, with one pole of a strong permanent magnet. Are all the materials equally magnetized by this treatment? Determine which end of each object has a north pole.

Self Check

1. What word describes materials which are attracted strongly by a magnet?
2. Name two materials other than iron and steel which are strongly attracted by a magnet.
3. How did the north pole of a magnet get its name?
4. If two cylindrical magnets are placed side by side on a table with the two south poles together, what happens?
5. How could you magnetize a screwdriver?
6. What kind of metal will make a nonpermanent magnet?

Discussion Questions

1. If you had only one, unmarked magnet, how could you find which end was the N-pole?
2. If you had two magnets, one marked and the other not, how could you use the marked magnet to find the N-pole of the other?
3. Your school laboratory probably has a number of rectangular steel magnets. As a result of careless use, some may not be perfectly magnetized. How could you test them to see which are in poor condition?
4. How might a watch become magnetized? Why is this bad for the watch?

Magnetic Behavior in Terms of Magnetic Fields

9–5 Magnetic effects operate at a distance. Anyone who has worked with magnets realizes that they need not actually touch objects in order to attract them. Indeed magnetic attraction operates through many materials, such as air, glass, aluminum, and water, as well as through empty space.

The influence of a magnet extends infinitely out into space. The region of influence surrounding a magnet is known as its **magnetic field**. It is strongest near the magnet and decreases with distance. Since a magnet has two poles, a magnetic field exerts a force on both ends, creating a moment that tends to turn the magnet.

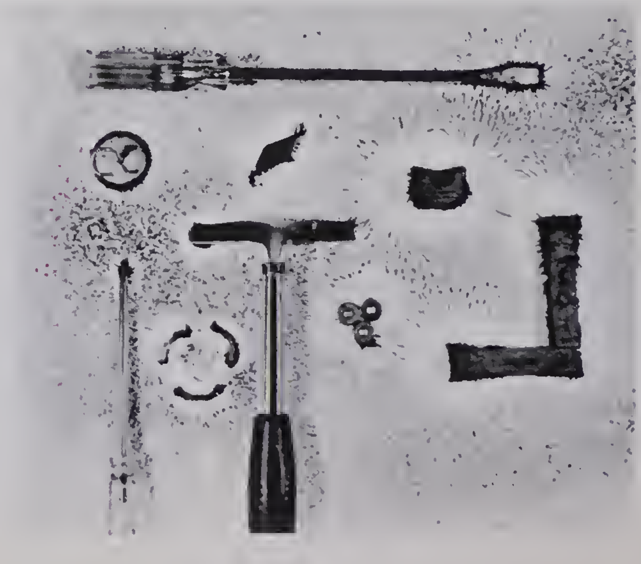
Do It Now

Over how great a distance can you demonstrate the effect of a magnetic field? Suspend a strong permanent magnet by a long thread, then try to influence it with another strong magnet several feet away. Can you accomplish this at a distance of 1 m? 3 m? 5 m?

9–6 Magnetic fields can be measured and graphed. Although you cannot feel or see a magnetic field, there are simple ways of studying it. Place a horizontal sheet of paper or glass just above a magnet. Then sprinkle iron filings on the paper. You will find that they arrange themselves into a definite pattern like the ones in Figs. 9–1, 9–2, and 9–4.

The iron filings form a pattern that is densest near the poles, where the field is

Figure 9–4 These objects were magnetized and a piece of glass was placed on them. Iron filings were next sprinkled on the glass.

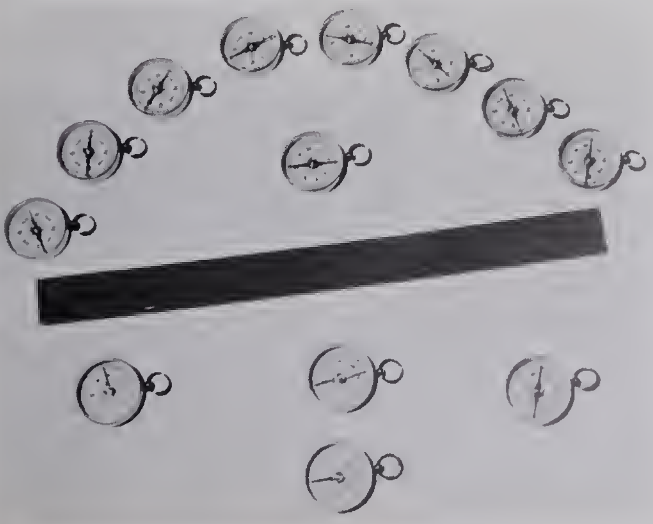


most intense. Although the field varies in intensity throughout the region surrounding the magnet, it is nevertheless smooth and continuous. There are no strips of space where the field is zero sandwiched between strips having a strong field. Though the iron filings arrange themselves into lines, the magnetic field itself is not separated into lines.

A magnetic field can also be explored with a small magnetic compass. If a compass is placed at several successive points near a magnet, it orients itself according to the magnetic field at these points, as in Fig. 9–5. This suggests that a magnetic field has direction as well as magnitude and is therefore a vector quantity. The direction of a magnetic field is defined as the direction of the force on a north-seeking or N-end of a pivoted compass needle.

The term "lines of force" is used frequently in describing magnetic fields. A **line of force** is defined as the path which would be taken by an isolated N-pole (if there were such a thing) completely free to move in a magnetic field. Thought of in this way, a "line of magnetic force" does have meaning. However, it is best not to think of a magnetic field as consisting of lines of force, since, as was noted previously, a magnetic field is continuous.

Figure 9–5 A magnetic field can be explored with a compass. Here compass headings are shown in many positions. The upper row suggests a line of force of the field. The lower compasses are placed at random.



Do It Now

1. Explore the field of a permanent magnet with finely ground iron filings. As you tap the paper more and more, you find that the lines which the filings form become more and more distinct and separate. Soon you will have substantial areas where there are no iron filings. Can you demonstrate that there is actually a magnetic field even in this "no-iron-filings" space?
2. Roughly sketch the pattern of the iron filings, then remove them. Use a small magnetic compass to explore the magnetic field. Move the compass in a direction indicated by its N-pole, so that it "follows its nose." Does this path coincide with the former location of the lines of iron filings?

9–7 Magnets consist of domains.

If you wish to know *why* there are magnetic forces, you cannot get an answer. Magnetic forces exist, just as gravitational and electrical forces exist. Scientists can describe their behavior, but cannot account for them.

There are other "why" questions about magnetic materials, however, that scientists can answer by formulating a theory about how magnetic forces act. Some questions you might ask are:

Why are some materials more magnetic than others?

Why does a bar magnet, when broken in the middle, seem to have new poles at the two new ends?

Why can you make a magnet by stroking a piece of iron with another magnet?

Why does heating or vibrating destroy a magnet?

Why does a magnet attract an unmagnetized piece of iron?

The theory that answers these questions best is this: Ferromagnetic materials, whether in a magnetized or unmagnetized condition, are made up of atoms which are

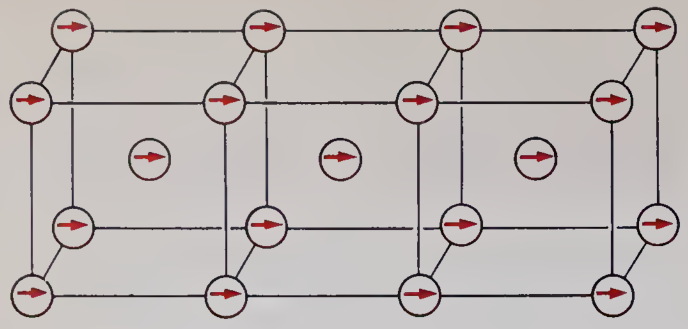
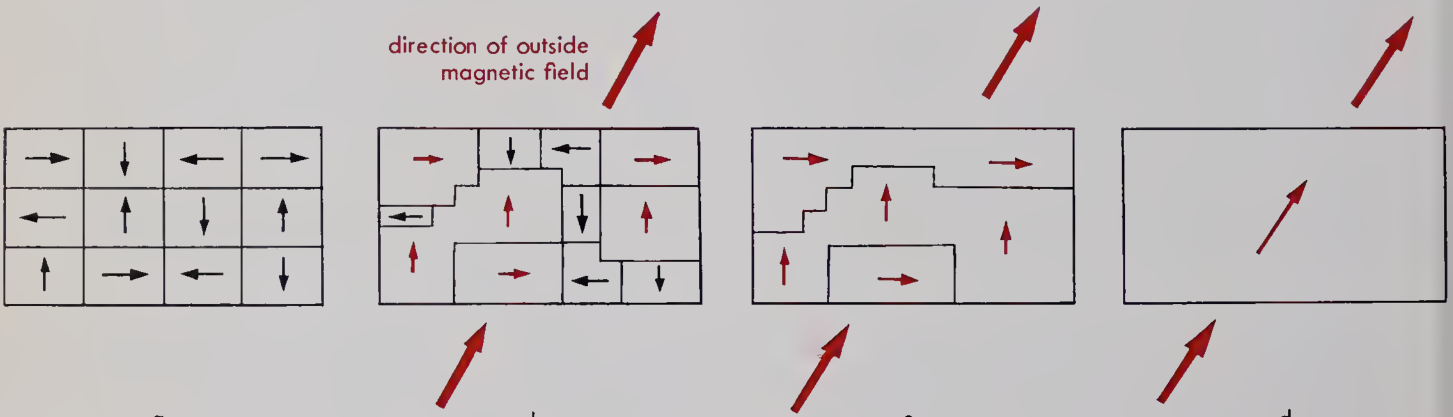


Figure 9–6 In a crystal of iron there is an atom at each corner of the cube plus one atom at the middle. In this portion of an iron crystal all of the atomic magnets have lined up so that the direction of their field is from left to right. Many millions of atoms lined up in this way constitute a domain.

themselves tiny magnets, each with a north and a south pole. Iron, like most solids, is a crystalline substance, with an orderly arrangement of atoms (Fig. 9–6). Each atom is a magnet and therefore is surrounded by a magnetic field. Since it is a magnet, each atom is influenced by the magnetic fields of the other atoms. Consequently, many little atomic magnets line up parallel to each other. Millions of atoms arranged like this form a magnetic **domain**. Each domain is perfectly magnetized; that is, all its atomic magnets are lined up in the same direction. Domains are extremely small, and a crystal of iron contains many of them.

In an iron crystal there are six directions of magnetism in which the field of a domain ordinarily may point. In Fig. 9–6 the direction is to the right. The other directions are to the left, up, down, toward the back, and toward the front. In an unmagnetized piece of iron, the domains are lined up in various directions, with the result that their fields cancel each other (Fig. 9–7a). Now suppose someone strokes the unmagnetized iron with a magnet. The outside field due to the magnet exerts a force on the domains in the iron. Some of the stages in the process are shown in Fig. 9–7.

Figure 9–7



a.

In a small piece of unmagnetized crystal of iron, the domains have a random arrangement, and their fields cancel each other. The diagram here is a simplified one, since it leaves out domains that have their directions out of the paper and down into it, and since it represents all of the domains as being the same size and the same shape.

b.

Here an outside field has been applied in the direction shown. The force exerted causes the domains indicated by red arrows to grow at the expense of others. The growth occurs because atoms near the boundaries flip over as they experience the double effect of the outside field and the field of the nearby domains.

c.

Now the boundaries have spread so that only the domains that are partly in the direction of the outside field are left. If the outside field is strong enough, the last step is to turn all of the magnetized atoms so that they line up with the outside field. This means that they must have a direction that is not one of the six usual magnetic directions of the iron crystal; therefore, this step is the hardest of all.

d.

The iron is now magnetized as strongly as it can be. All of the magnetic atoms are lined up in the direction of the outside field.

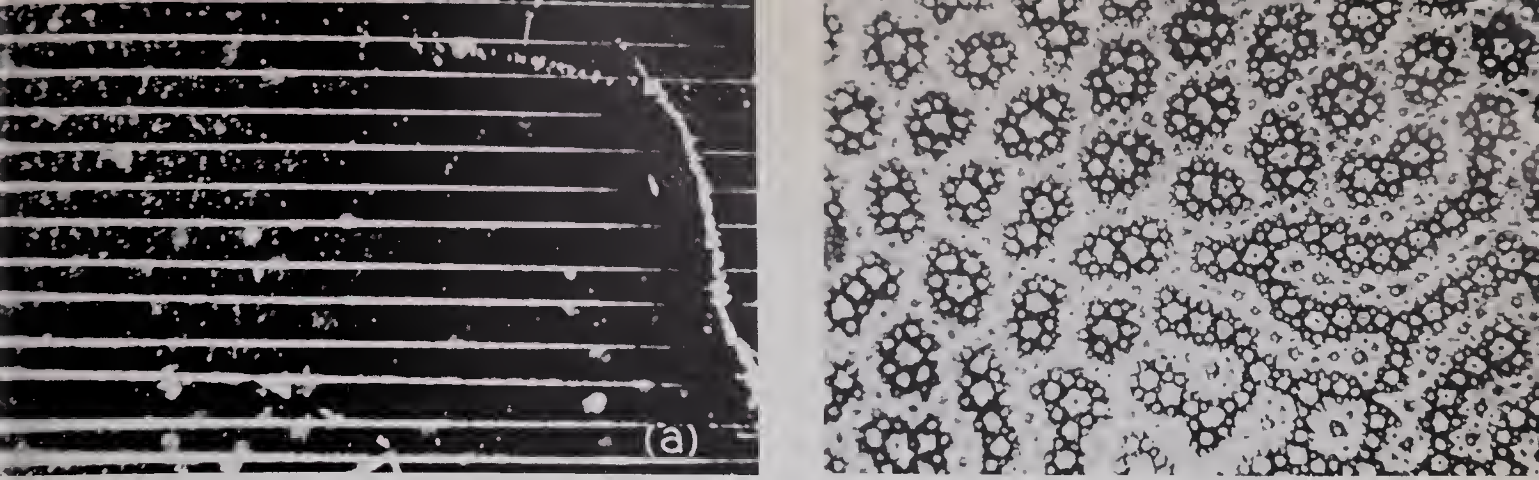


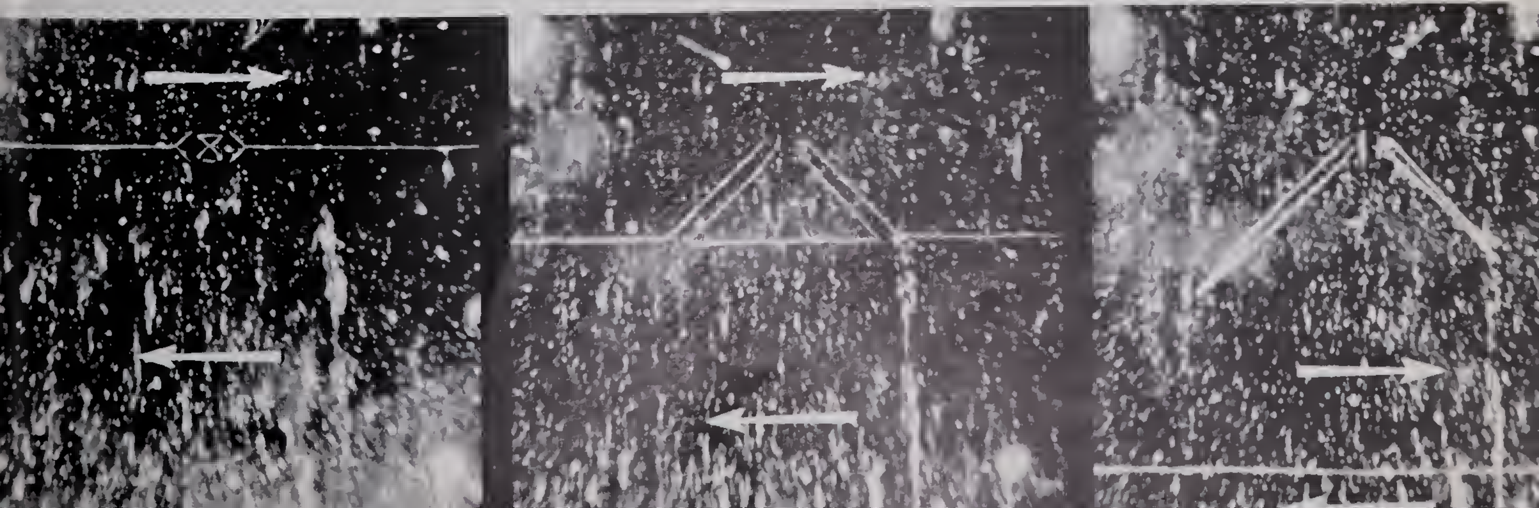
Figure 9–8 These photographs, taken through a microscope, show the domains in cobalt. In **a** you see the domains lengthwise; in **b** you see their ends. To outline the domains, magnetite was ground to a fine powder and mixed with a liquid. A very thin layer of the liquid was put on the cobalt surface. The bits of magnetite floated to the edges of the domains, outlining them. See page 370 for a photograph of domains in a nickel-iron alloy.

The domain theory certainly helps to explain how you can magnetize a piece of iron by stroking it with a magnet. However, more proof than this is needed before you should accept the theory as a good one. Two pieces of evidence have helped to establish the domain theory.

Look at Figs. 9–1 and 9–2. Where are the iron filings thickest? At the edges of the magnets. This fact gave scientists an idea. Suppose you used finely ground bits of a magnetic substance and put them on a very smooth piece of a ferromagnetic material. They might outline the edges of the domains. This experiment was tried, and it worked.

Figure 9–8a shows the domains in a piece of cobalt. Notice that they are parallel strips. In cobalt, magnetic atoms normally line up in two directions only. In this picture they are to the right or to the left. Figure 9–8b is an end view of the cobalt domains. Here each domain has a field that is either up out of the paper or down into it, as seen in the picture. It is possible, using a microscope, to watch the changes in the domains as a magnetic field is applied. Figure 9–9 shows a domain boundary moving down in an iron alloy because of the presence of an outside magnetic field directed to the right. This kind of photograph makes it possible to measure

Figure 9–9 **a** A piece of silicon iron was placed on a microscope stage and covered with tiny bits of magnetite floating in liquid. The magnetite floated to the boundary between two domains, forming the horizontal straight line. Pay no attention to the white flecks. **b** and **c** An external magnetic field, directed to the right, was applied. Under its influence plus that of the field of the upper domain, magnetic atoms in the lower domain flipped over near the boundary. The bits of magnetite floated along as the boundary moved. The two slanting domains left behind represent a crystal imperfection.



the sizes of domains. In an unmagnetized piece of iron, domains range in volume from 10^{-6} to 10^{-2} cm^3. Thus a domain in this material contains from 10^{17} to 10^{21} atoms.

The other piece of experimental evidence supporting the domain theory is this: While a piece of iron is being magnetized by a slowly increasing magnetic field, a listening device attached to a loudspeaker is put in the field. At intervals a sharp crack is heard. It seems likely that each crack signals a sudden change in the boundary of a domain.

9–8 The domain theory explains magnetic behavior. The questions asked on p. 219 can be answered by using the domain theory. Some materials are more magnetic than others because their atoms are stronger magnets. In a permanent magnet the domains are lined up throughout the magnet; therefore, breaking the magnet merely turns it into two complete magnets.

When you stroke a piece of iron with the north pole of a magnet, the south ends of the magnetic atoms in the domains are attracted and tend to line up in the direction in which the north pole is moving. Vibrating or heating weakens a magnet by shaking up the domains and converting them to more nearly equal size, with random magnetic orientation.

Why does a magnet attract an unmagnetized piece of iron? At first the domains making up the unmagnetized nail are not lined up. However, when the south pole of a magnet is brought near the nail, those domains with their fields pointing toward the magnet grow at the expense of the others. Consequently the nail becomes a temporary, somewhat imperfect magnet with a north pole at the top and a south pole at the bottom. The process is called **magnetizing by induction.** The nail is a magnet because of the presence of a magnetic field. When you remove the nail from the permanent magnet, most or all of the domains of the nail return to their original random arrangement. If the field is very strong, the nail may retain some permanent magnetism even after the original field is gone.

Self Check

1. What is the name of the region in which a magnet produces an influence on other magnets or magnetic materials?
2. How large is the region of influence of a magnet?
3. Describe two ways in which you could show the presence of a magnetic field.
4. Is there a magnetic field between the "lines" of iron filings around a magnet?
5. What is the direction of a magnetic field at a point?
6. Why is iron a magnetic material?
7. What is a magnetic domain?
8. How are the domains arranged in an unmagnetized piece of material?
9. What happens to the domains of an unmagnetized ferromagnetic object when it is placed in a magnetic field?
10. Why does heating destroy a magnet?
11. Describe a method by which magnetic domains can be observed.
12. What is magnetization by induction?

Discussion Questions

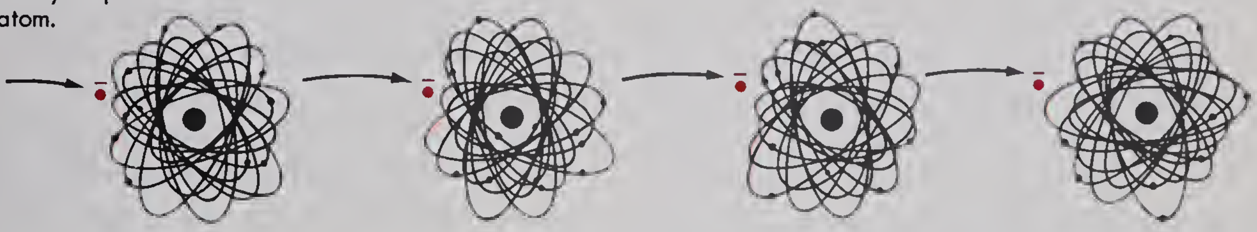
1. Why must you not stroke a bar of iron with another magnet with a back-and-forth motion if you wish to make a magnet of the bar?
2. When a scientist wishes to study magnetic domains, why does he put the powdered magnetite in a liquid instead of scattering it over the surface of the iron?

Electromagnetic Behavior

9–9 Electric current in a wire is a flow of electrons. An electric current in a wire consists of a flow of electrons, as suggested in Fig. 9–10. When an electric current exists within a substance, electrons are passed along from atom to atom, or from molecule to molecule. The moving electrons are part of the substance itself. In good conductors of electricity, some electrons of each atom are loosely attached to the rest of the atom and are free to move from one atom to the next. They therefore are called **free electrons** (p. 87). It is not necessary to supply electrons to an electric circuit. It is necessary only to supply energy to move the electrons through the substance of which they are a part. The energy may be supplied by a dry cell.

Figure 9–10 The diagram below shows copper atoms with a normal arrangement of twenty-nine orbiting electrons per atom. When an extra "free" electron is added at the left, other electrons in turn are passed along to succeeding atoms at the right. The result is a general drift of free electrons from left to right.

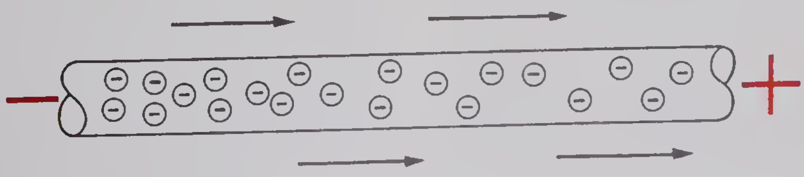
Extra electron is added to the 29 already possessed by copper atom.



The first atom cannot handle 30 electrons, so it passes one along to the second atom.

Similarly, the second atom passes an electron along to the third; the third atom, to the fourth; etc.

This diagram is of a segment of copper (or other metal) wire. Here only the free electrons are shown. Under ordinary conditions there is a general shifting of free electrons among atoms. However, when there is electric current, there is also a general drift of electrons from one end toward the other. Notice that the electrons are caused to move by an excess of electrons at the left and a deficiency of electrons at the right; that is, the left end of this wire has a negative charge as compared with the right end. If this were not so, the electrons would not move.



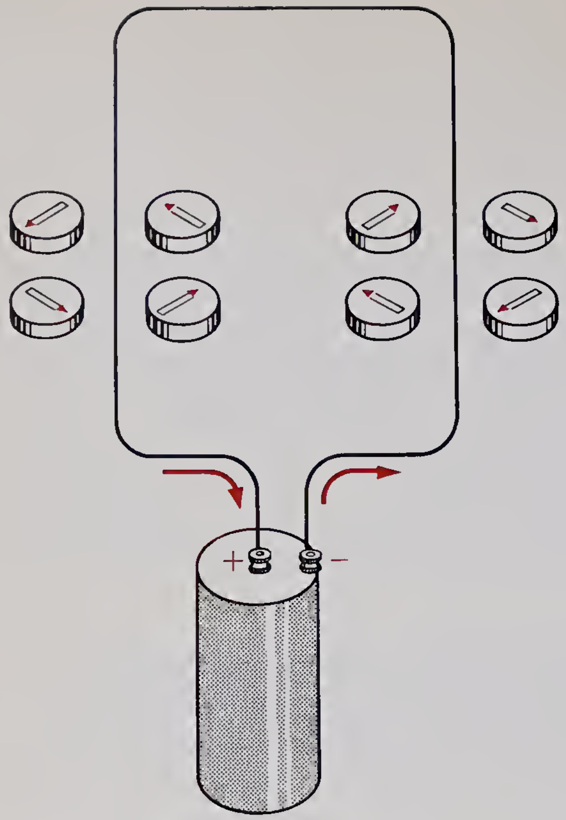


Figure 9–11 A simple circuit like this one can be used to show the existence of a magnetic field around a current.

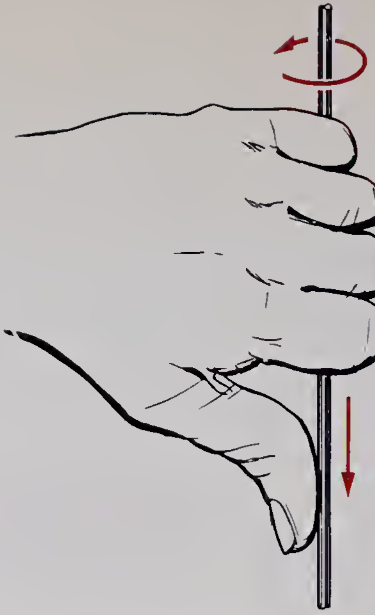


Figure 9–12 The left-hand rule is a useful one for determining the direction of a magnetic field around a current. The thumb points in the direction of electron flow; the fingers point in the direction of the field (the direction of the force on a N-pole).

9–10 A magnetic field surrounds an electric current. In Fig. 9–11 a wire is connected across the terminals of a fresh dry cell. As a result there is a large current in the wire. Compass needles or iron filings surrounding the wire indicate the presence of a magnetic field.

It is important to note that the magnetic lines of force are in the form of circles surrounding the wire. As you might suspect, the field is strongest near the wire and becomes weaker as the distance increases. Surprisingly, the field strength is inversely proportional to the distance, rather than to the square of the distance.

Although the magnetic field surrounding an electric current has no poles — no beginning or end — it does have direction. The direction of a magnetic field has been defined as the direction in which the north end of a compass needle points. The series of compass needles in Fig. 9–11 show the direction of the field surrounding a current. The direction depends on the direction in which electrons flow. A useful way to remember this relationship is the **left-hand rule**, illustrated in Fig. 9–12. The thumb points in the direction of electron flow while the other fingertips point in the direction of the force on a north magnetic pole.

Do It Now

Connect the ends of a wire to a fresh No. 6 dry cell as shown in Fig. 9–11. Before exploring the magnetic field around the current, predict its direction by the left-hand rule. Is your prediction verified? Reverse the connections so that the electrons flow in the opposite direction. Does the field reverse?

9–11 Current in a loop of wire produces a magnetic field. What happens to the direction of a field if the straight wire of Fig. 9–11 is bent into a circular loop? The left-hand rule is applied to various

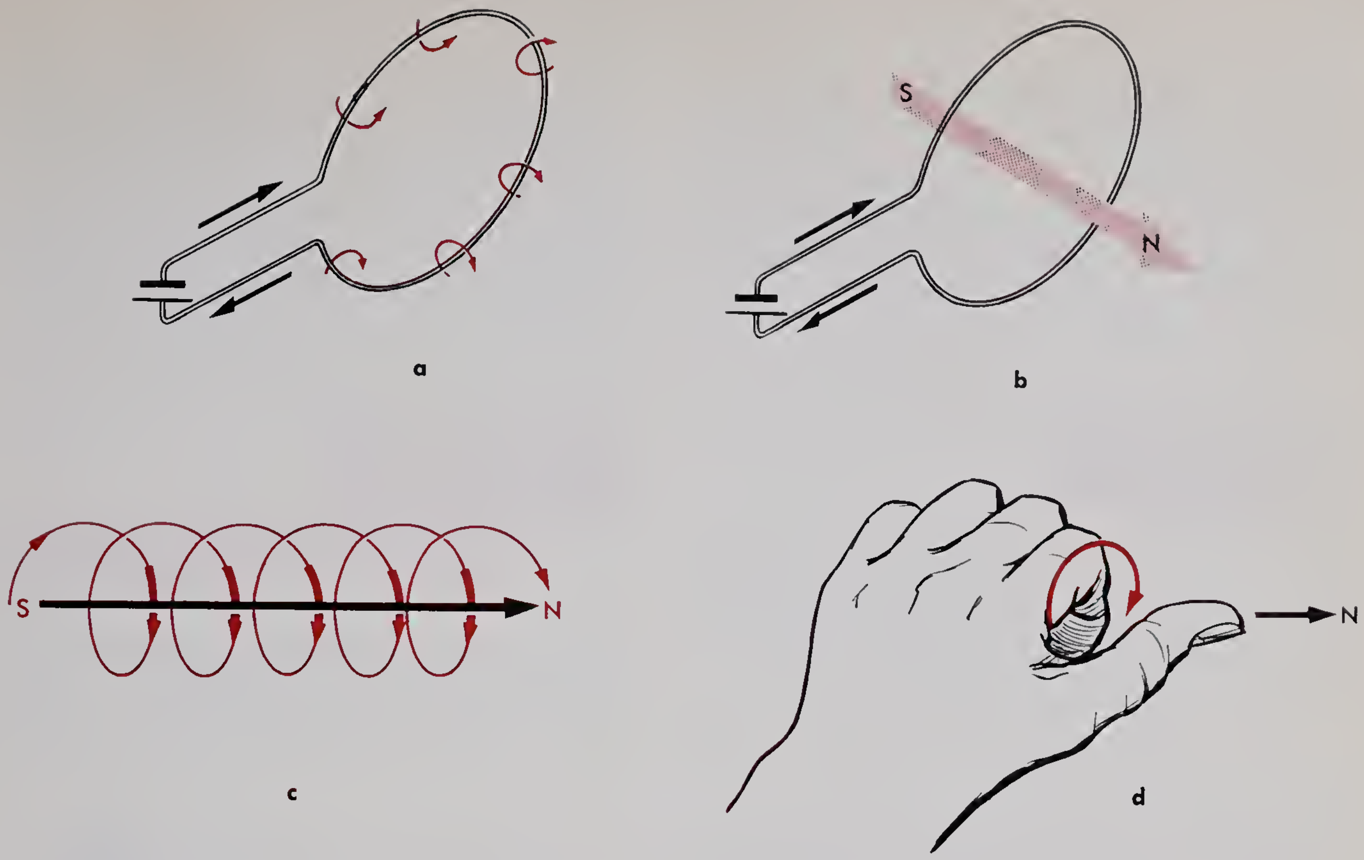


Figure 9–13 In **a** the magnetic fields surrounding many portions of the loop are shown. Note that they all provide a component of a magnetic field from left to right inside the loop. As a result, there is a magnetic field within the loop as shown in **b**. If the wire is wound into a coil, as in **c**, the coil becomes a magnet with a N-pole at the right. The left-hand rule can be modified to indicate the direction of the field within a current loop, as shown in **d**. The fingers indicate the direction of electron flow, while the thumb points in the direction of the resulting magnetic field.

parts of a loop in Fig. 9–13a; you can see that the field in each segment of the loop follows the same direction on the inside of the loop. Therefore, a compass needle placed in the center of the loop, as shown in Fig. 9–13b, points in a direction perpendicular to the plane of the loop. If the wire is coiled, as in Fig. 9–13c, the apparatus begins to resemble a magnet, with a north and a south pole. Although you can use the left-hand rule on each turn of the coil to find the direction of the north pole of the electromagnet, it is simpler to use another left-hand rule in this case. This time the fingers point in the direction of electron flow, while the thumb indicates the direction of the magnetic field, as shown in Fig. 9–13d.

A coil of wire prepared for the purpose of producing a magnetic field is called an **electromagnet**. Usually the coil is wound on an iron core. When the current is turned on, the magnetic field due to the current causes the core to become magnetized by induction. The result is that the total magnetic field due to the coil plus the core is several thousand times as great as that of the coil alone.

The strength of an electromagnet depends on the magnitude of the current, the number of turns, the diameter and length of the coil, and the material of the core. A material like iron, which may multiply the strength of the magnet by 1,000 or more, is said to have a high relative permeability. Cobalt multiplies the magnet strength by about 170; it has a lower relative permeability than iron. In general, the **relative permeability** of a substance is the amount by which the strength of an electromagnet is multiplied when the substance is used as a core. A coil with many turns of wire is called a **solenoid**.

Do It Now

Repeat the activity shown in Fig. 9–11, this time using a coil of a few turns of wire rather than a straight wire. Were you able to predict the direction of the field within the loop?

9–12 Electromagnets are used to produce mechanical forces. By using large currents in many turns of wire and core materials of high relative permeability, electromagnets which exert great mechanical force on ferromagnetic materials can be made. Among the most impressive are the lifting magnets used in foundries and scrap iron yards.

One of the most interesting applications of the electromagnet is a sucking coil, which, when current exists in it, can lift a piece of unmagnetized iron or steel. Sucking coils are used not only for chimes, but also to operate electrically controlled valves like those in automatic washing machines.

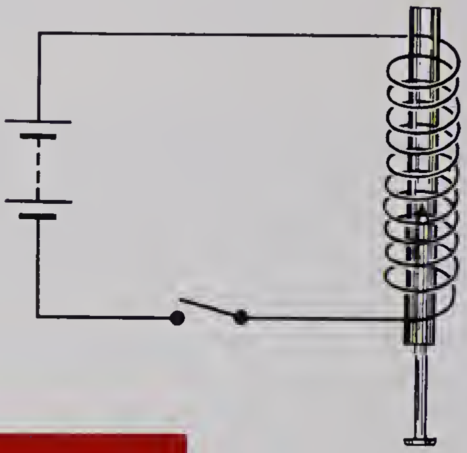
The uses of electromagnets mentioned so far depend on the great force they can exert on iron and steel objects. Less obviously, their usefulness depends on the ease with which they can be turned on or off. This characteristic is of great importance in many communications devices.

A current in a coil of wire can be used to make artificial bar magnets. If you produce a large current in the coil and place a piece of steel within it, the intense magnetic field will align the magnetic domains in the steel and make it a magnet by induction. A suitable alloy will retain its magnetism indefinitely.

The point was made earlier that a permanent magnet can be made by bringing a suitable ferromagnetic material under the influence of another magnet. Now that you know more about magnetic fields, it is more accurate to say that the magnet is made by placing the material in a magnetic field.

Do It Now

You can make a sucking coil as shown in the sketch. Use 40 to 60 turns of No. 22 insulated wire wrapped around a short length of 6 mm glass tubing. When operated from a 3- to 6-volt battery, this should lift a short piece of nail or soft iron wire while current exists in the coil.



Self Check

1. What is an electric current in a wire?
2. What is the source of electrons in a current?
3. How can you show that an electric current is surrounded by a magnetic field?
4. Describe the magnetic field surrounding an electric current. Where are its north and south poles?
5. A magnetic compass is allowed to come to rest in a north-south direction. A wire is placed over it, and connected so that the electrons flow from north to south. Will the compass deflect clockwise or counterclockwise as seen from above?
6. A spool of insulated wire is set with its axis vertical, and a flow of electrons is sent through the wire. The direction of electron

flow, as seen from above, is counterclockwise. In which direction is the magnetic field inside the coil?

7. A solenoid is made by winding turns of wire around a glass cylinder 5 cm in diameter. Without changing the size of the cylinder, name three ways in which the field inside the cylinder can be made more intense.
8. What are some practical applications of the ability of electromagnets to produce mechanical force?

Discussion Questions

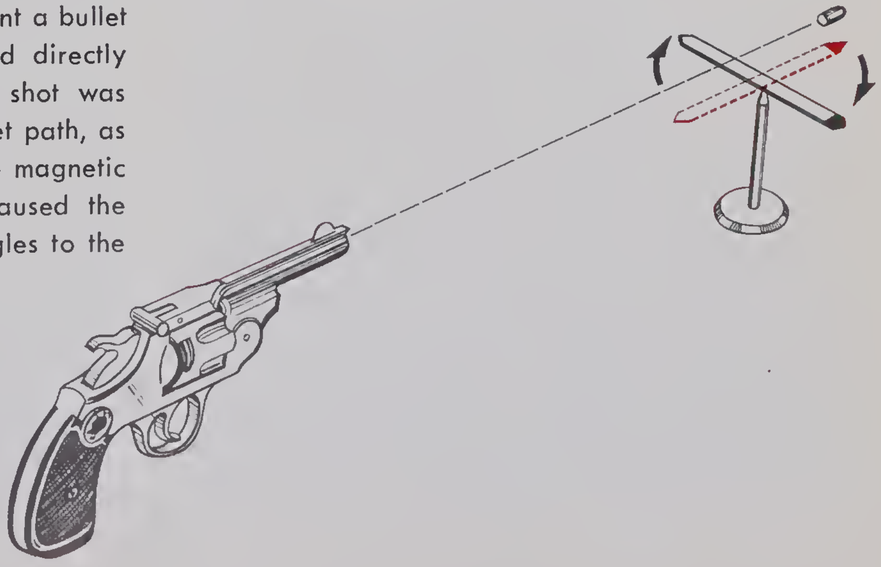
1. How does it happen that the rule for the direction of magnetic field around a moving charge is the same as that for the magnetic field around a current in a wire?
2. A strong bar magnet has a hole drilled through the center. A straight conductor is inserted through the hole and insulated from the magnet. The magnet is free to rotate with the wire as the center of rotation. If there is an intense current in the wire, would you expect the magnet to rotate? Explain.
3. If there were such a thing as an isolated magnetic pole, how would you expect it to behave in the vicinity of a conductor with an intense current?
4. What is the direction of a magnetic field due to electrons in a television picture tube? (These electrons leave the back end of the tube, travel its length, and strike the picture end of the tube from the inside.)

Moving Electric Charges Underlie Magnetism

9–13 A magnetic field surrounds any moving charge. You have seen that an electric current in a wire is surrounded by a magnetic field. Since an electric current consists of moving charges, you might ask, "Will any moving charge produce a magnetic field, even if the charge is not in a wire?" Figure 9–14 illustrates an imaginary experiment that could answer the question. You fire a bullet possessing a large electric charge above a magnetic compass. Here is a moving charge, and if it produces a magnetic field, the compass needle will be deflected.

The charged bullet experiment would be difficult to perform, but physicists have discovered how to shoot electrons through highly evacuated tubes, and they find that these moving electrons do produce a magnetic field, which can be detected outside the tube. A moving charge, in a wire or not, is surrounded by a magnetic field.

Figure 9–14 In this imaginary experiment a bullet with a large negative charge was fired directly over a magnetic compass. Before the shot was fired, the needle was parallel to the bullet path, as shown by the dotted lines. However, the magnetic field surrounding the moving charge caused the needle to shift to a position at right angles to the direction of motion of the charged bullet.



Do It Now

(WARNING — An oscilloscope is a delicate instrument. If not carefully handled, it is also dangerous; it can give you a severe electric shock. This activity should be done only under teacher supervision.)

With the approval of your instructor, remove the housing from an oscilloscope. Adjust controls so that a single spot is produced on the screen. Now bring a pole of a magnet near the neck of the tube. Does the magnet have any effect on the electron stream? Does this indicate that moving electrons are surrounded by magnetic fields?

9–14 Moving electric charges produce magnetism. In 1820 André Ampère suggested that the basic cause for magnetism might be found in the movement of charged particles within the atom. Of course, the techniques of that day were hopelessly incapable of testing such a hypothesis. Within the last few decades, however, more and more evidence indicates that this is indeed the case. Surely there is an abundance of charged particles within the atom. Can their movement account for the magnetic behavior of matter?

Electrons move in elliptical orbits around the nuclei of atoms. This movement of electrons constitutes electric current in a loop and therefore produces a magnetic field within the loop. In addition, there is evidence that each electron rotates on its axis. A spinning electron is a charge in motion and therefore also creates a magnetic field. In every atom twice as many magnetic fields exist as electrons, since each electron produces two fields, one for orbital motion and one for spin.

In most atoms the various fields cancel each other out because they are lined up in random directions. In ferromagnetic materials, however, the fields do not cancel each other entirely. Each iron atom has four electrons whose spin-magnetism is uncanceled. While the motion of electrons in their orbits may account for some of the magnetism of ferromagnetic materials, the spin seems to be much more important.

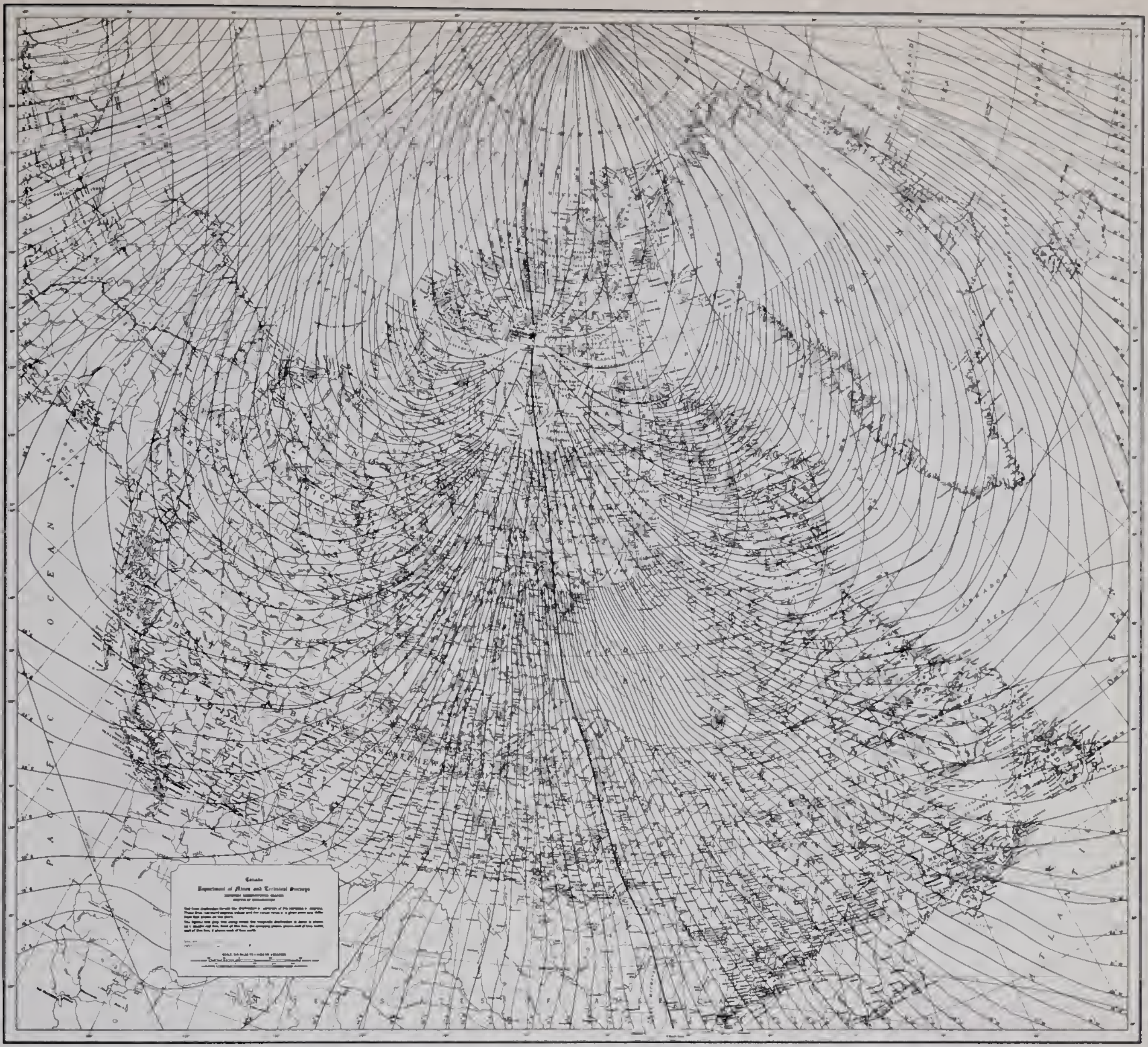
The nucleus of an atom also spins, and since the nucleus contains positive charges, a magnetic field is created, but the effect is so small that it is not noticeable for any reasonable quantity of matter.

So strong is the field of each atom that in magnetic materials, interaction among adjacent atoms causes large clusters of them to line up their magnetic axes parallel to each other. These are the magnetic domains referred to on p. 219.

9–15 The earth has a magnetic field. What makes a suspended magnet point north and south? The simplest theory is that the earth itself is a magnet and that the compass needle is demonstrating the law of magnets. However, the earth is not a magnetized chunk of iron, like a bar magnet. It has an outer rocky mantle about 1800 miles deep. Below that is the liquid part of the core, about 1300 miles thick, surrounding the solid center. Scientists believe that motion of charges in the liquid part of the core create the earth's magnetic field. Because of its great size, the speed of moving charges in such a loop need only be of the order of magnitude of 2×10^{-4} m/sec. What kind of charges exist in the core? What keeps them moving? At present these are questions for which scientists have no final answer.

Movements of charged particles in the earth's atmosphere also contribute slightly to earth magnetism. Variations in the movements of charges within and around the earth cause both regular and irregular variations in earth magnetism.

The variations in earth magnetism from place to place and from time to time make it impossible to pick a small spot and say, "This is the location of the magnetic pole of the earth." However, in the Arctic region of North America there is an area in which a magnetic compass needle points almost straight down. Therefore this area is called the North Magnetic Polar Area. In the



Distribution of magnetic declination in Canada for 1960.

Figure 16–15 The curved lines on this map connect places where the compass declination is the same. They are called isogonic lines.

southern hemisphere there is a similar South Magnetic Polar Area.

A magnetic compass needle points in the direction of the earth's magnetic field. In general, this is a north-south direction, but because the earth's field is irregular and not centered at the geographic poles, there is usually a difference between compass direction and true north. The angle between the two is called the **angle of declination**, or **angle of variation** (Fig. 9–15).

Do It Now

Use a compass outdoors to determine magnetic north. Compare this direction with true north as indicated by the North Star or by accurate local maps. How does this comparison check with magnetic variation where you live? Obtain information about magnetic variation from a local airfield.

9–16 How good is the theory? People once thought that magnetism and electricity were two quite different things. Today it is known that an electromagnet can be made by sending current through a coil of wire. Scientists believe that the magnetism of a permanent magnet can be accounted for by the motion of charges in the atoms, and that the earth's magnetism results from the motion of charges inside the earth and in the atmosphere above it. Hence magnetism appears to be merely a consequence of the motion of charged particles and not a fundamental phenomenon of nature.

The idea that all magnetic effects are produced by charges in motion is a theory. The theory is a good one. Not only does it provide an explanation that agrees with observed facts, but it is simpler than any other theory that has been suggested. When more than one theory agrees with the facts, scientists prefer to choose the simplest one.

The final test of a good theory is its ability to predict what will happen in new situations and its continuing ability to agree with newly discovered facts. Scientists of today are investigating problems that involve using the theory of magnetism. What gives cosmic ray particles their great energy? What causes the northern lights? Why are there belts of intense radiation around the earth? Perhaps when these questions are answered satisfactorily, there may be changes in the theory of magnetism, but to date all observations seem to support it.

Self Check

1. If you fire a negatively charged bullet and watch it recede, what is the direction of the magnetic field which surrounds it? What if the bullet bears a positive charge?
2. If you charge a large, flat, plastic top negatively, in what direction will the magnetic field be if the top spins horizontally, clockwise as seen from above? What if the top were charged positively?
3. What two types of motion within the atom contribute largely toward the magnetic properties of atoms? Which is more important?
4. If motions within the atom can account for the magnetic properties of atoms, why are not all materials magnetic?
5. What is believed to be the major cause of the earth's magnetism?
6. What is believed to be the cause of all magnetic phenomena?

Discussion Questions

1. Is the North Magnetic Pole Area a N-pole or a S-pole? Explain.
2. A student finds that a magnetic compass points in different directions when he places it in different positions on a table. Can you think of an explanation?
3. Iron pipes, steel girders, and other large steel objects which remain stationary usually acquire a distinct magnetic polarity. Explain.
4. What fact or facts about magnetism have not been explained by the theories described in this chapter?

Chapter Summary

Magnets attract ferromagnetic materials, which include iron, nickel, and cobalt, and some of their alloys and compounds. Paramagnetic materials are weakly magnetic, and diamagnetic materials are repelled by magnets. Magnets have two kinds of poles, usually called north and south. Like poles repel each other; unlike ones attract each other. The force between magnetic poles is directly proportional to the product of the strengths of the poles and inversely proportional to the square of the distance between them. A permanent magnet is made when a suitable ferromagnetic material is put into a strong magnetic field.

A magnet is surrounded by a magnetic field, extending theoretically to infinity. The strength of the field decreases rapidly as the distance from the magnet increases. If another magnet is placed in the field, it experiences a mechanical moment. The direction of a magnetic field at any point is the direction of the force on a north pole at that point. Magnetic fields are continuous.

According to modern theory, atoms of magnetic substances are individual magnets, millions of which are lined up together to form microscopic domains. The substance is magnetized when its domains are lined up with their fields parallel.

An electric current in a wire consists of a flow of free electrons. Every electric current is surrounded by a magnetic field. The direction of this field can be found by using the left-hand rule. An electric current in a coil of wire produces a magnetic field along the axis; the direction of the field can be found by application of the left-hand rule. The strength of the field depends on the size of the current, the length of the coil, the number of turns, and the relative permeability of the core. Electromagnets are used to produce mechanical forces. The magnetic field around a current is employed to make modern permanent magnets.

All moving charges produce magnetic fields, even when they are individual charges in space. Moving charges within the atom produce the magnetic character of matter; moving charges within the liquid part of the earth's core are believed to be the principal cause of terrestrial magnetism. All magnetic phenomena can be explained in terms of the magnetic fields produced by moving electric charges.

Vocabulary

magnetism (*p. 216*)
ferromagnetic (*p. 216*)
paramagnetic (*p. 216*)
diamagnetic (*p. 216*)
north pole (*p. 216*)
south pole (*p. 216*)
law of magnets (*p. 217*)
magnetic field (*p. 218, 224, 227*)
line of force (*p. 219*)
magnetic domains (*p. 219, 220*)
magnetizing by induction (*p. 222*)
electric current (*p. 223*)
free electrons (*p. 223*)
left-hand rules (*p. 224, 225*)
electromagnet (*p. 225*)
relative permeability (*p. 226*)
solenoid (*p. 226*)
orbiting electrons (*p. 228*)
electron spin (*p. 228*)
angle of variation, of declination (*p. 229*)

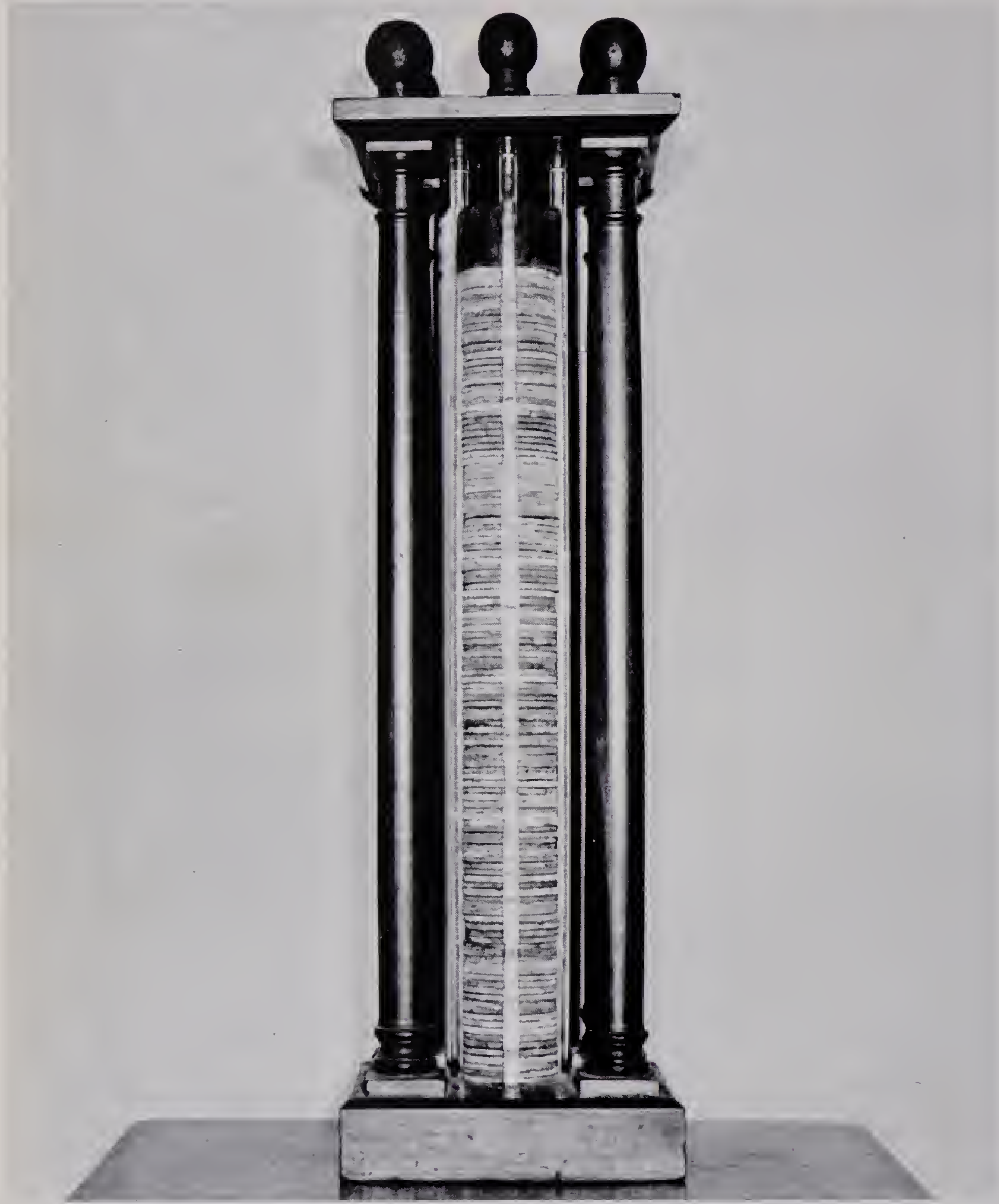
Discussion Questions

1. If you had two apparently identical bars of steel, one a permanent magnet, the other unmagnetized, and had no other equipment, how could you tell which is magnetic?
2. What is the difference between a permanent magnet and a completely magnetized piece of iron?
3. How would you state a rule for determining the direction of magnetic field around a moving positive charge?
4. If there were such a thing as an isolated magnetic pole, how would you expect it to behave in the vicinity of an air-core solenoid?
5. An air-core solenoid has N-magnetism at one end and S-magnetism at the other. Does this mean that the field produced by the solenoid has a beginning and an end?
6. It sometimes is said that a magnetic compass above a magnetic pole simply spins on its axis. From what you know of magnetism, what is your reaction to this statement?
7. Would you agree with the statement that all magnets are electromagnets? Why?

Work on Your Own

1. Study the history of the study of magnetism. Suggested references: Gilbert, William, *De Magnete,* Dover. William Gilbert was one of the first to study magnets. He wrote this book in Latin about 1600. It has been translated into English and makes very interesting reading.
   Taylor, Lloyd W., *Physics, the Pioneer Science,* Houghton Mifflin, 1941.
   Bitter, Francis, *Magnets: The Education of a Physicist,* Doubleday, 1959.
2. Use a reasonably powerful permanent magnet to explore dry garden soil. Are there any components of the soil which are attracted by the magnet? Do you think such materials are iron or compounds of iron? Could you devise a chemical test to confirm your suspicion?
3. Are there any alloys of metal which are magnetic in spite of their names, or which are nonmagnetic even though their names suggest that they are magnetic? (Suggestion: consider noncorrosive alloys, nickel alloys, and various kinds of stainless steel.)
4. Examine a telephone receiver (earphone) or the speaker unit from a radio or a record player. Is there evidence that these devices involve permanent magnets?

CHAPTER 10



Courtesy of Dickinson College, Carlisle, Pennsylvania.

This battery was constructed in 1800 by Alessandro Volta and was eventually presented by him to Joseph Priestley. It is now in the museum of Dickinson College, Carlisle, Pennsylvania.

Electric Energy and Electric Circuits

Imagine you are a laboratory assistant to Professor Alessandro Volta at the University of Pavia in Italy in the year 1800. You may see him demonstrate a simple electric cell using copper, zinc, and salt water. Possibly you help him set up one of his famous "Volta-piles" — a stack of disks of silver and zinc separated by salt-soaked pads. With these he gives curious observers a tingling electric shock.

In 1800 you would have seen the dawn of a brand new age — the age of electric current. Volta's discovery of the electric battery paved the way for a long series of physical and chemical experiments. These led to today's complex and varied electric circuits. Furthermore, the use of electric batteries opened up many other lines of scientific investigation. It is small wonder that scientists have named one of electricity's most fundamental units — the volt — after the Italian physics professor.

In this chapter you will study electric currents, electric energy, and electric circuits.

Electric Currents

10–1 Electrons move through wires from negative to positive. In Chapter 9 you learned that an electric current in a wire consists of a flow of electrons. From what you know about the forces of attraction and repulsion of electric charges, it is obvious that electrons move through a wire from its negative end toward its positive end, as was shown in Fig. 9–11. All this would be simple and straightforward if it were not for a historical accident.

Early experimenters with electricity theorized that an electric current was made up of something moving. In the eighteenth century a successful printer named Benjamin Franklin became interested in electricity and did much basic research in the field. He suggested that there was only one kind of electricity. When an object had more than a normal supply, Franklin proposed it be called **positive** ; if the object had less than a normal supply, he called it **negative** . Logically, then, Franklin's electricity flowed from a region of excess to one of scarcity – from positive to negative.

The idea that the direction of a current was from positive to negative became widespread because the concept of electrons was not formed until the end of the nineteenth century. Some textbooks still refer to current direction in this way; this is termed "conventional current." However, all physicists agree that currents in wires consist of a flow of electrons from negative to positive. Throughout this book, references to current direction in wires will be in the modern and accurate sense — electrons flowing from negative to positive.

10–2 Electrons move through wires slowly. When a switch in an electric light circuit is closed and the circuit completed, the lamp appears to glow immediately. This suggests that electricity travels with infinite speed.

Now imagine a circuit with a switch in St. John's, Nfld. and an electric lamp in Vancouver, B.C., some 3000 miles away. When the switch is closed, electrons are flowing through the lamp within a small fraction of a second. Actually, electric energy is transmitted over conductors at a speed approaching the speed of light.

Electrons themselves, however, do not move at the speed of light in an ordinary circuit. In the typical household circuit, electrons do not exceed an average speed of a centimeter or so per second. At this rate it would take years for a particular electron to drift across the transcontinental circuit. The situation is similar to a mile-long freight train starting up from a standstill. Within a few seconds the slack has been taken out of the train and the caboose is actually moving. If this surge of motion is felt by the caboose in 10 sec, the surge velocity is

$$v_s = \frac{s}{t} = \frac{1 \text{ mi}}{1/6 \text{ min}} = \frac{1 \text{ mi}}{1/360 \text{ hr}}$$
$$= 360 \text{ mi/hr}$$

If the train is heavily loaded, however, it might take 15 min for any one car to move 1 mi. In this case the car velocity v_c is

$$v_c = \frac{s}{t} = \frac{1 \text{ mi}}{15 \text{ min}} = \frac{1 \text{ mi}}{1/4 \text{ hr}} = 4 \text{ mi/hr}$$

This comparison indicates how the electrons in an electric current may move at a very low speed, while the surge of electric energy is vastly greater.

10–3 Electric energy can flow through liquids and gases. In this discussion electric current has been described as a flow of electrons. This is true of electric energy flowing in solid materials. However, electric energy often flows through liquids and gases, too. In these cases, the flow of electric energy consists of negative ions (often electrons themselves) flowing in one direction, and positive ions — protons, for example — moving in the opposite direction. (See Chapter 4 for more information about ions.) In hydrogen gas, for example, an electron may be removed from an atom and move toward the positive terminal of a gas-discharge tube, as in Fig. 10–1. In this case, the remainder of the atom is a proton. Because of its positive charge, it moves toward the negative electrode. The hydrogen gas has been ionized.

Most gases can be ionized under proper conditions. One or more electrons are removed from the atom, converting the remainder into a positive ion.

Many solutions are ionized. For example, a solution of common table salt, NaCl, is actually a mixture of Na^+ ions and Cl^-

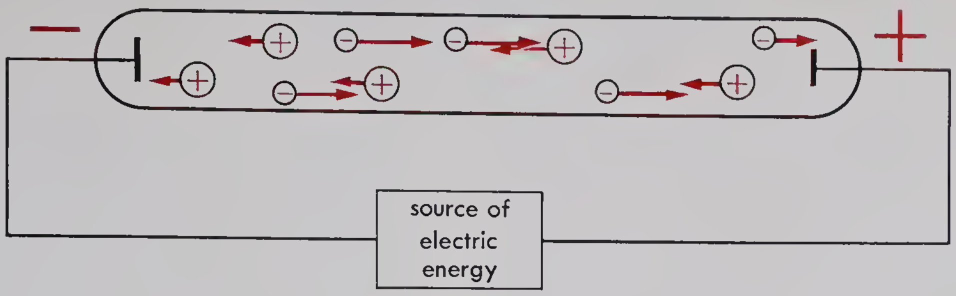


Figure 10–1 This gas-discharge tube contains hydrogen gas at very low pressure. The gas is ionized, so electrons are free to move away from the remainder of the atom — in this case, protons. Electrons move much more rapidly than protons.

ions in water. In solution each molecule of sulfuric acid, H_2SO_4, ionizes into two hydrogen ions (actually protons) and one sulfate ion, SO_4^{--}. An ionized solution is called an **electrolyte**.

10–4 Moist earth conducts electric current. Nearly all ordinary soil contains considerable quantities of water. Furthermore, this water contains dissolved mineral matter, and much of this is ionized. As a result, moist earth conducts an electric current moderately well. This is important in the understanding of many electric circuits, and also for reasons of personal safety.

Moist earth is commonly used as a substitute for one of the two wires in a simple telephone circuit. For safety it is important to remember that of the two wires of every household electric circuit, one is deliberately and firmly connected to moist earth; that is, it is **grounded**. If you handle the "live" or ungrounded wires or defective appliances while standing on moist earth or concrete, or have your hand touching a water pipe, you may become a part of the circuit and receive a painful or fatal shock. The best precaution, of course, is not to handle "live" electric wires or defective appliances. As an added safety measure, do not make even minor electrical repairs unless you have disconnected the circuit.

Do It Now

If an ohmmeter is available, use it to measure the resistance of moist earth. To do this, drive two metal stakes into the ground a few feet apart, and measure the resistance between the two stakes. Make further tests by varying the length of the stakes or the distance between them and by testing different kinds of soil.

10–5 Some materials conduct electrons better than others. When electric current exists, no atom is left with too few or too many electrons for any great period of time. A free electron lost from one atom is replaced by another electron from a nearby atom. But, as you learned in Chapter 4, not all atoms and molecules possess free electrons which can drift in this manner. Those which have many free electrons and therefore permit easy drifting of electrons from one atom to another are good **conductors**. Those which have very few free electrons to drift are **insulators**.

Because the metal element copper is a good conductor, is not too expensive, and also because it can be easily soldered, it is the most commonly used material for electric wires. Copper wire often has a white or silvery appearance. This is because it is sometimes coated with tin or alloyed with other metals. One result of this is to make the treated wire easier to solder.

Nearly all metals are relatively good conductors, and most nonmetals are quite poor ones. A few of the familiar metals, listed with the better conductors first, are: silver, copper, gold, aluminum, zinc, tungsten, brass, iron, tin, and steel.

Many common materials are very poor conductors of electrons. Typical examples of such insulators are rubber, glass, mica, dry cloth, paraffin, dry air, most oils, celluloid, and distilled water.

It is a mistake to think of all materials as being either conductors or insulators. It is more accurate to think of conductors as conducting electrons very well and insulators as doing so very poorly. Another way of putting this is to say that conductors offer very little resistance to the flow of electrons, while insulators offer very great resistance. Between these two extremes are many common materials which offer moderate resistance to the flow of electric charge.

Self Check

1. Under what conditions can an electric current be defined as a flow of electrons?
2. When an electric current is something more than this electron flow, what is it?
3. Distinguish between current as electron flow and "conventional current." How did this confusing situation occur?
4. How can a surge of electric energy travel at speeds approaching the velocity of light, while the electrons themselves drift along at only a few centimeters per second?
5. Why is it misleading to think of materials as falling into two distinct classes: conductors and insulators? What is a better way to interpret variations in ability to conduct?
6. What does it mean to say that a wire is grounded?
7. What is the difference between an atom of a given element and an ion of the same element?

Discussion Questions

1. It has been stated that Volta's development of the chemical electric cell marked the opening of the age of electric current. How would you uphold the argument that there were essentially no electric circuits before that time? Can you find any exceptions to this argument?
2. Explain why it is that the earth itself constitutes a serious safety hazard.

Measuring Electric Currents

Since current is electron flow, a simple system for measuring current would be counting electrons. Although this method has the appeal of simplicity, it is impractical because electrons are so difficult to count. Furthermore, the numbers of electrons involved in common currents are fantastically large. For example, an ordinary flashlight lamp has about three billion billion electrons passing a given point per second!

10–6 Electric currents produce forces on each other. Figure 10–2 illustrates a simple experiment which you can do at school or at home. The two hanging wires are arranged so that they possess intense electric currents either in the same direction or in opposite directions. When you try this, you will see that when the currents are in the same direction, the wires attract one another. When the currents are in opposite

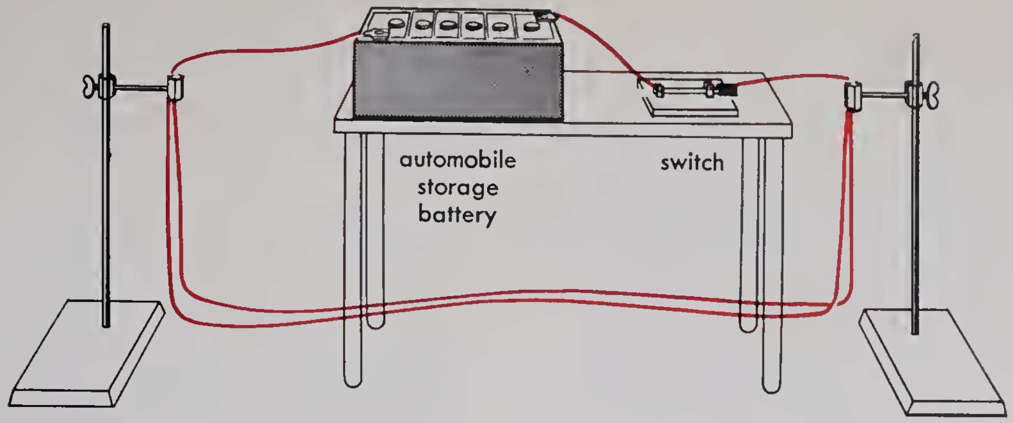


Figure 10–2 Two wires are fastened together at each end and bent, so that they are parallel for about 50 cm and are about 1 cm apart. When the switch is closed, the two wires move together slightly. If the circuit is changed so that the two currents in the wires are in opposite directions, the wires move apart.

directions, the wires repel. Actually, this is a magnetic effect and takes place because every electric current is surrounded by a magnetic field.

The diagram in Fig. 10–3 shows how the two parallel currents exert a force on each other. The fields surrounding the two currents are circular, following the left-hand rule (p. 224). Here they are drawn as though they contained a series of small permanent bar magnets. When the two currents are in the same direction, adjacent bar magnets have unlike poles next to each other and therefore attract. This accounts for the force pulling the two conductors together. If the currents are in opposite directions, the force between the conductors is one of repulsion.

Needless to say, the field surrounding a current does not consist of tiny bar magnets, and the diagram of Fig. 10–3 is not to be interpreted literally. However, it does make the forces between electric currents more understandable. Also it helps you to remember that currents in the same direction attract each other, and currents in opposite directions repel. The force between two such conductors in air depends on the magnitude of the currents, the length of the conductors, and the distance between them.

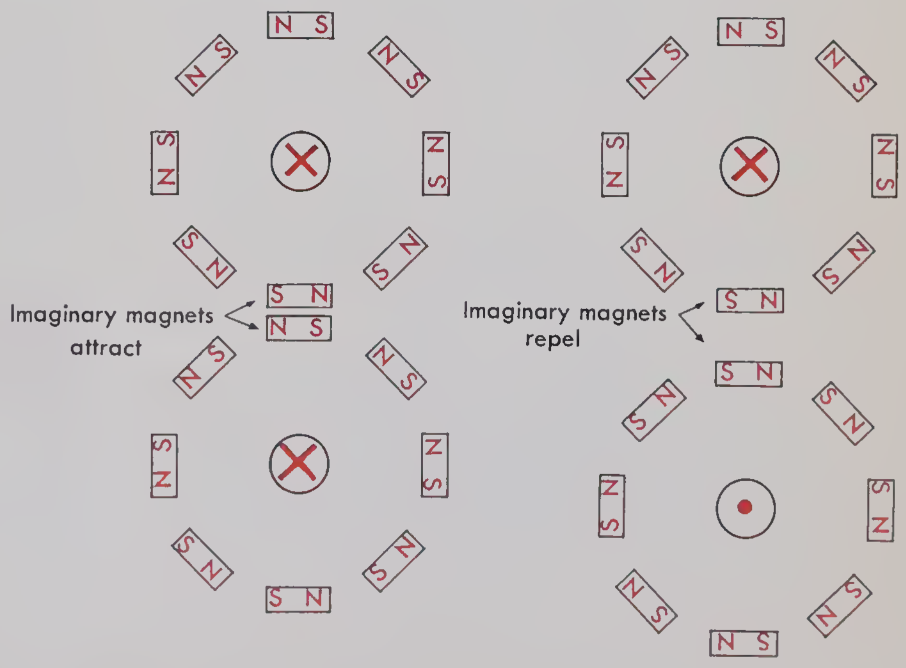


Figure 10–3 These diagrams will help you to understand the forces existing between conductors with electric currents. Currents in the same direction attract, while those in opposite directions repel. The small circles represent cross-sections of wires that are perpendicular to the page. A dot means that electrons are coming up the wire toward you; a cross means that they are moving into the page.

Do It Now

Prepare a coil of fairly stiff copper or brass wire by wrapping the wire around a cylinder 3–5 cm in diameter. As a result you should have a loose-wound "spring" of 10–15 turns and 15–20 cm long. Suspend this by one end and arrange it so that the other end dips into a vessel of mercury. Now connect an automobile storage battery so that it produces a current in the spring. Does the spring react? If you experiment patiently, you can prepare a startling demonstration. The coil will contract due to current and thus lift its lower end out of the mercury. Explain the operation of this device.

10–7 The ampere is defined in mechanical terms. The forces between electric currents provide a useful way to establish a unit of current. Indeed, it is so useful that it constitutes the scientific definition of the ampere used by the International Committee for Weights and Measures and is accepted as the legal standard in most civilized nations. The **ampere** (**A**) may be defined as that constant current which, if present in each of two very long conductors one meter apart in empty space, produces a force of 2×10^{-7} newton for each meter of length.

In practice, the "very long conductors" are actually carefully wound coils of wire. At Standards Laboratories around the world measurements of this type are made with painstaking care. Conductors are kept at a constant temperature by a water jacket and in a glass case to avoid air currents. Adjustments are made by remote control, and observations are made through telescopes.

10–8 The coulomb is defined in terms of the ampere. The fundamental unit of electric current — the ampere — provides a useful method of defining a quantity of charge more conveniently than by counting electrons. When an ampere of current exists in a circuit, there is during each second one coulomb of charge passing a given point in a circuit. Expressed in equation form:

$$Q = It.$$

where Q is charge in coulombs, I is current in amperes, and t is time in seconds. Thus a coulomb is an ampere · second.

The coulomb is named in honor of Charles A. Coulomb (see p. 84), who, during the latter half of the eighteenth century, carried on fundamental experiments about the behavior of electrically charged objects. The quantity of charge in one coulomb is equal to that of 6.24×10^{18} electrons. (See p. 85.) However, the coulomb is used as a measure of either negative or positive charge. The coulomb is actually an extremely large charge, much larger than is ordinarily found in common practice. Therefore it is common to use a small fraction of a coulomb, such as a **microcoulomb** (10^{-6} C), in laboratory work. The abbreviation for microcoulomb is μC.

Self Check

1. In a solenoid, do adjacent loops of wire attract or repel each other when there is current in them? Why?
2. Define the ampere.
3. Define the coulomb.
4. What charge is transferred by a current of 3.0 A in 40 sec?
5. What current will be required to transfer 12 C in 3.0 sec?

Problems

Ⓐ 1. A given storage battery delivers a current of 8.0 amperes. During each minute how many coulombs of charge pass a given point in the circuit to which the battery is connected?

2. During the brief period of 1.0 millisecond when a certain electronic photoflash lamp operates, it is known that a charge of 0.050 coulombs is transferred. What is the average current?

3. How many electrons pass through the lamp in the problem above?

B

4. An atom of copper has a mass of 1.05×10^{-22} g. During the electroplating of copper, 2 electrons must be supplied for each copper atom that is plated. How much copper will be plated if a current of 2.0 A flows for 10 min?

Discussion Questions

1. Early workers in electricity did not know whether a current consisted of a flow of negative particles in one direction, a flow of positive particles in the other, or both. Why was it impossible for them to solve this problem in terms of the forces which conductors exert on each other?
2. It is true that a coulomb passing any point in a second constitutes a current of one ampere. Then it must also be true that an ampere is one coulomb per second. Why cannot this be used as a definition for the ampere rather than the one on p. 394?
3. In a current balance why are coils used instead of long, straight wires?
4. The coulomb is an enormous unit of charge, but the ampere is not a very large current. An electric toaster, for example, uses about nine amperes of current, a flow of nine coulombs every second. Why are there not enormous electrical forces when so many coulombs of charge move?

Electric Fields

10–9 An electric field surrounds an electric charge. Like charges repel each other; unlike charges attract. This occurs even though the charged objects are not touching each other. Thus electric charges must have an influence in the region surrounding them; that is, the region surrounding an electric charge is somehow altered because of the presence of the charge. This region of influence is called an **electric field**. You are probably not surprised to find that an electric field is strongest near the charge which produces it, as suggested in Fig. 10–4. For small, spherical, charged objects the strength of the electric field varies inversely as the square of the distance from the object.

An electric field can be detected by the fact that it produces a force on a charge which happens to be in it, as in Fig. 10–5. The field has direction, too. Its direction is defined as the direction of the force which it produces on a positive charge.

The idea of an electric field is a very useful concept in understanding many things about electricity. You will be using this

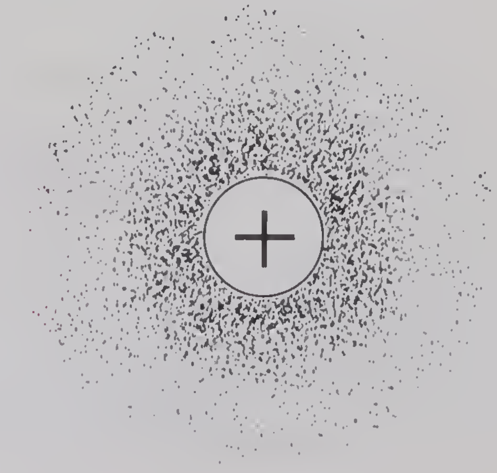


Figure 10–4 This diagram indicates that the electric field around a charged object is strongest near the object. For small, spherical objects, the field strength is inversely proportional to the square of the distance from the object. The dots do not represent physical objects but merely the field strength.

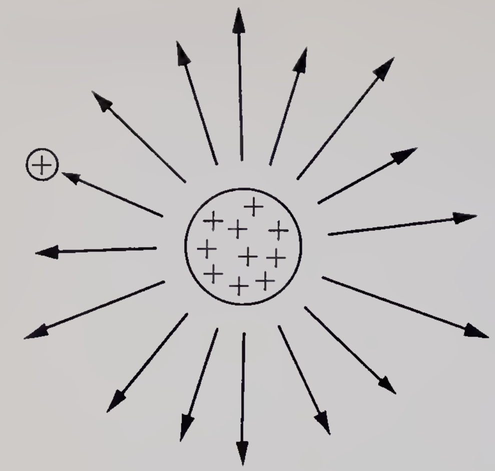


Figure 10–5 This diagram shows the direction of the electric field surrounding a positively charged object. The field produces a mechanical force on a charged object in the field.

concept repeatedly in many areas of physics. Be sure you understand these statements:

1. Every charged object is surrounded by an electric field.
2. An electric field is strongest near the charged object which produces it. In many simple cases, the strength of an electric field follows the inverse square law.
3. An electric field exerts a mechanical force on a charged object.
4. The direction of an electric field is the direction of the force it produces on a positive charge.
5. An electric field has no mass or substance; it can exist in a vacuum.

10–10 Forces due to an electric field can be calculated. A most practical way to detect and measure an electric field is by means of the mechanical force which it exerts on a charged object. Here simple experiments with electrostatics and common sense coincide: the force of an electric field on a charged object varies directly with the intensity of the field and with the magnitude of the charge. Expressed mathematically:

$$F = EQ$$

where F is force produced, E is intensity of electrical field, and Q is magnitude of electric charge. This equation can be rearranged and used to provide a definition of **electric field intensity**:

$$E = \frac{F}{Q}$$

Hence the intensity of electric fields is expressed in terms of force per unit charge, usually as newtons per coulomb or newtons per electron.

This defining equation makes possible the solution of many problems involving electric fields.

Since electric field has both *intensity* (magnitude) and *direction,* it is a vector quantity. Hence electric fields can be added vectorially.

10–11 Electric fields can be described in terms of potential energy. Physicists, like all scientists, constantly experiment to find answers to problems and explanations for observed phenomena. Sometimes, however, the experiments they would like to do are extremely difficult, or they may be impossible. Then a good technique is a thought experiment, one which is carried out entirely in the mind — usually with the help of pencil and paper. This method was widely used by Albert Einstein and others in developing extremely abstract ideas about relativity. After all, if you want to do an experiment with an airplane traveling at half the speed of light, it *must* be a thought experiment.

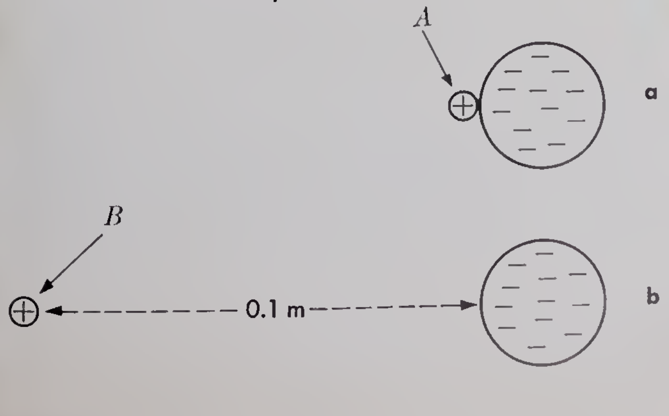
Here is a thought experiment to help illustrate the concept of electric potential energy. Imagine a large, negatively charged object and a tiny, positively charged object, as in Fig. 10–6. The large, negatively charged object is fixed in position so that it cannot move. Of course these objects are attracted to each other by electrostatic force.

Now think of them as being extremely close to each other. If you pull the positively charged object out a distance of 0.1 m, you must exert a force through that distance; that is, you must do mechanical work. From Coulomb's law, you know that the force exerted through the distance varies, hence, the calculation of the energy required is difficult to do with no mathematics beyond algebra. Nevertheless, assume that the work needed to separate the objects is, say, 0.05 J.

While moving the positively charged object from *A* to *B*, you have performed work on it. Where is this energy you have put into the system? Surely it is not lost. From the principle of conservation of energy, you know that this same quantity of energy will be released when the positively charged object is permitted to return from *B* to *A*. It is evident, then, that the entire system possesses more energy when the positively charged object is at *B* than when it is at *A*. That is, the positively charged object has more potential energy at *B* than at *A*. In this case, the difference in potential energy is equal to the work done to move the charged object, or 0.05 J.

10–12 The volt is defined in terms of energy per unit charge. Suppose that the object that was moved from *A* to *B* in Fig. 10–6 has a charge of 10 μC. The work done to move it was 0.05 J, and this is equal to the potential energy gained by the charge.

Figure 10–6 **a.** The negative charge here is comparatively large and is not free to move. **b.** The positive charge has been moved *against* the coulomb force of attraction a distance of 0.1 m. In this process a total of 0.05 J of work has been expended.



Therefore:

$$\text{Potential energy gain between } A \text{ and } B = 0.05 \text{ J for } 10\ \mu\text{C} = \frac{0.05 \text{ J}}{10 \times 10^{-6} \text{ C}}$$

$$\text{Potential energy gain per unit charge} = \frac{5 \times 10^{-2} \text{ J}}{10^{-5} \text{ C}} = 5 \times 10^{3} \text{ J/C}$$

In other words, if a 1-C charge had been moved from *A* to *B*, it would have required 5000 J of work to make the move, and the charge would have acquired 5000 J of potential energy. The potential energy difference between *A* and *B* for a 1-C charge is called the **potential difference** between the two points, and is measured in joules per coulomb, or **volts (V)**. If 1 J of energy is required to move a charge of 1 C from one point to another in an electric field, the potential difference between the two points is 1 volt:

$$1 \text{ V} = 1 \text{ J/C}.$$

Notice that the potential difference is always measured between two points.

This definition can be stated in mathematical form:

$$V = \text{Energy}/Q$$

where *V* is the potential difference in volts, energy is in joules, and *Q* is the magnitude of the electric charge in coulombs. This equation makes possible the solution of problems concerning electric potential.

Do It Now

The energy potential of a charged object with respect to another object with similar charge increases as the two objects get closer together. When would the potential energy between the two be zero?

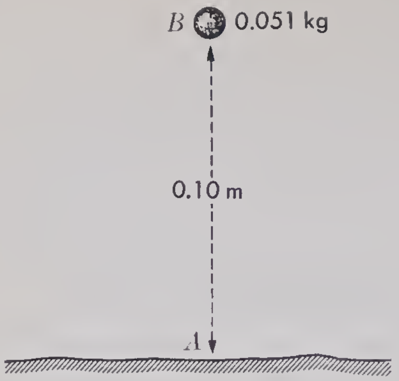


Figure 10–7 A mass of 0.051 kg raised 0.10 m above ground level has a potential energy of 0.050 J. That much energy was required to raise it, and that quantity of energy will be released when the mass is lowered, or when it falls.

10–13 Electric and gravitational fields can be compared. The relationships in the thought experiment of Sections 10–11 and 10–12 are strikingly similar to energy potentials in gravitational fields. In the earth's gravitational field the ground level can correspond to point *A* in Fig. 10–7. The direction of the field, of course, is down. If a mass of 0.051 kg is raised a distance of 0.10 m, the work involved is found by Work = *Fs*. In this case, the force is the weight of the object whose mass is 0.051 kg. Since weight (force) = *mg*, the force in the work equation is:

$$F = 0.051 \text{ kg} \times 9.8 \text{ m/sec}^2 = 0.50 \text{ N}$$

Therefore:

$$\begin{aligned}\text{Work} &= 0.50 \text{ N} \times 0.10 \text{ m} = 0.050 \text{ N} \cdot \text{m} \\ &= 0.050 \text{ J}\end{aligned}$$

This is the energy involved in raising the object 0.10 m above the ground. This is also the energy which the object will deliver if permitted to fall back to the ground. Therefore, this object whose mass is 0.051 kg has 0.050 J more potential energy at point *B* than it does at point *A* (ground level). The potential difference between points *A* and *B* is 0.050 J ÷ 0.051 kg = 0.98 J/kg.

When you think about gravitational fields, you are accustomed to thinking of ground level as having zero potential energy. Of course, this really is not true. A rock does work falling into a hole and therefore loses energy. It is more accurate and more useful to think of ground level not as a zero point for potential energy, but as a *reference point*.

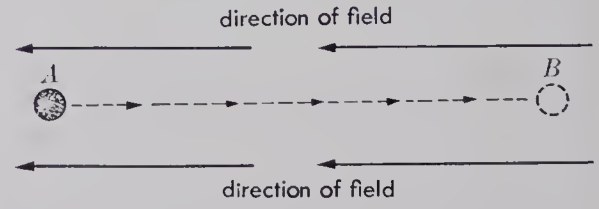
10–14 The electron volt is a unit of particle energy. Suppose an electron is placed in an electric field, as shown in Fig. 10–8. The direction of the field has been defined as the direction of the force on a positive charge. Therefore the electron, being negative, will travel against the field if it is free to move. As the electron moves, it accelerates because the field continues to exert a force on it. The electron gains kinetic energy. Suppose that the potential difference between points *A* and *B* is 10 volts. The kinetic energy of the electron at *B* can be calculated.

$$\begin{aligned}V &= \text{Energy}/Q \\ \text{Energy} &= QV\end{aligned}$$

The charge on an electron is 1.6×10^{-19} C. Therefore:

$$\begin{aligned}\text{Energy} &= 1.6 \times 10^{-19} \text{ C} \times 10 \text{ V} \\ &= 1.6 \times 10^{-18} \text{ C} \times \text{J/C} \\ &\quad (\text{since } 1 \text{ V} = 1 \text{ J/C}) \\ &= 1.6 \times 10^{-18} \text{ J}\end{aligned}$$

Figure 10–8 The direction of the electric field is from right to left, but the electron at *A* will move in the opposite direction. It accelerates as it moves from *A* to *B*, gaining kinetic energy.



In particle accelerators or cloud chambers, physicists are often concerned with the energy of a single electron or proton that has been accelerated by a potential difference of a known number of volts. Because the joule would be an impractical unit to express the energy of an electron in motion, a new unit of energy, the **electron volt (eV)**, is used. It is defined as the energy acquired by an electron when it is accelerated through a potential difference of 1 volt. In the case described above, the electron has an energy of 10 eV when it gets to point *B*. In terms of joules, 1 eV is 1.6×10^{-19} J. Study Example 1 below.

EXAMPLE 1

In a particle accelerator an alpha particle moves through a field where the potential difference is 1.5 megavolts. What is the energy of the particle when it reaches its final speed?

Given: $V = 1.5$ megavolts $= 1.5 \times 10^6$ V

$Q = 2e$ (twice the charge of an electron)

To find: Energy

Solution: Energy $= QV$

$= 2e \times 1.5 \times 10^6$ V

$= 3.0 \times 10^6$ eV or 3.0 MeV (3.0 million electron volts), Answer

10–15 An electric circuit transfers energy. You have learned that an electric current is a flow of electric charges, and you have also learned about the energy which makes electric charges move. Now you are in a position to apply what you know to a simple electric circuit such as that in Fig. 10–9. Here the source of electric energy is a chemical electric cell rated at 1.5 volts. This means that the cell delivers 1.5 J of energy to each coulomb of charge which it forces through the circuit. As each coulomb flows through the lamp in the circuit, it delivers 1.5 J of energy to the lamp. This is converted into heat and light energy in the lamp filament. Thus the electric circuit permits the transfer of energy from the source (the cell) to the load (the lamp).

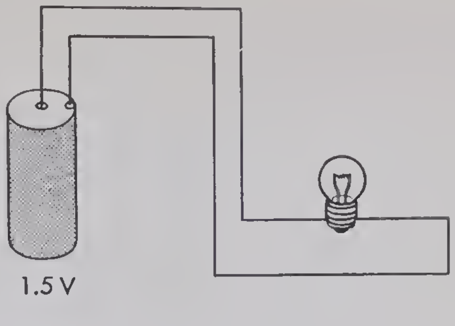


Figure 10–9 In this simple circuit the dry cell (the source of electric energy) delivers 1.5 J of energy to each coulomb of electric charge which goes through it. Each coulomb then delivers 1.5 J of energy to the lamp; this energy is converted into heat and light.

The volt (and the less desirable but very common term "voltage") is usually used to describe the potential difference between the two terminals of a cell or battery or between two specified points in an electric circuit. Literally, the volt describes the potential energy difference (in joules) per unit charge (in coulombs). In practice this is usually shortened to *potential difference.* Thus, the rating of 120 volts so common in household circuits means that the potential difference between the two supply wires is 120 volts. When a radio repairman uses a voltmeter and says "the potential here is 180 volts," he means that the potential difference between "here" and a selected reference point is 180 volts.

Many students think of the volt as being a unit of "electric pressure" or "electric force" or "electric power." Common though these interpretations are, none is correct. The volt is a unit of energy-per-unit charge; it is one joule per coulomb.

Self Check

1. If the force on a charge placed 1 cm from another charge is 0.08 N, what is the force when the separation is 2 cm?
2. If a large charged object attracts a small one with a force of 3 N, with what force does the small object attract the large one?
3. What is the direction of the electric field around a negatively charged sphere?
4. Define the volt.
5. A charge of 2 coulombs jumps a spark gap across which the potential difference is 1000 volts. What is the energy gained by the charge during the jump? What happens to this energy?
6. A storage battery is a source of energy. How much energy will a 12-volt battery give to a charge of 5 coulombs that passes through the battery?
7. What is the energy of an electron accelerated in an evacuated tube by a potential difference of 10,000 volts?
8. Why is it necessary to specify a reference point when describing the electric potential at a point in a field or at a point in a circuit?

Problems

A **1.** What is the force on a charge of 2×10^{-4} C when it is in an electric field whose magnitude is 0.1 N/C?

2. How strong would an electric field have to be to produce a force of exactly 1 N on a charge of 1000 μC?

3. If a charge of 30 μC moves from one point in an electric field to another and in so doing releases exactly 0.5 J of energy, what is the potential difference between the two points expressed in electric terms?

4. How much work is done by a 3.0-A current flowing for 10 sec between 2 points with a potential difference of 20 V?

5. What energy is possessed by a lithium nucleus (atomic number 3) which is accelerated by an electric field whose potential difference is 6.0×10^{5} volts?

6. What electric potential difference must a field possess to impart 15 meV of kinetic energy to an alpha particle?

B **7.** What is the acceleration of an electron in a field with a strength of 8.0 N/C? The mass of an electron is 9.1×10^{-31} kg.

8. What is the kinetic energy, expressed in mechanical units, of an electron which has been accelerated through a field whose potential difference is 50,000 V? At what speed would the electron be moving if the electron mass remained constant?

Discussion Questions

1. Like electric charges repel each other, while electric currents in the same direction attract each other. Do you consider this to be a contradiction?
2. What is wrong with the statement: The voltage at this point is 110?
3. Why is one of the most powerful particle accelerators called the bevatron?
4. Can you think of any disadvantages of referring to the volt as a unit of "electric pressure" or "electric force"? Are there any misunderstandings which might arise from this use?

Electric Circuits

10–16 Every electric current contains a complete path. Your everyday experiences have familiarized you with many electric circuits. One of these is the electric toaster, diagramed in Fig. 10–10a. The electric energy for this appliance is generated in a central power station and transmitted to the wall outlet into which the power cord is plugged. At first glance, a cord looks like a single connection, but it has two separate wires inside the same casing.

In the toaster, electric energy is converted to heat energy in the heating element, which is a length of wire made of a special alloy. In electric circuits, that portion which converts the electric energy — whether it changes the energy to heat, light, sound, magnetism, motion, or produces chemical reaction — is called the **load**.

Notice that the central power station, the connecting wires, and the toaster make up a complete path for electric current.

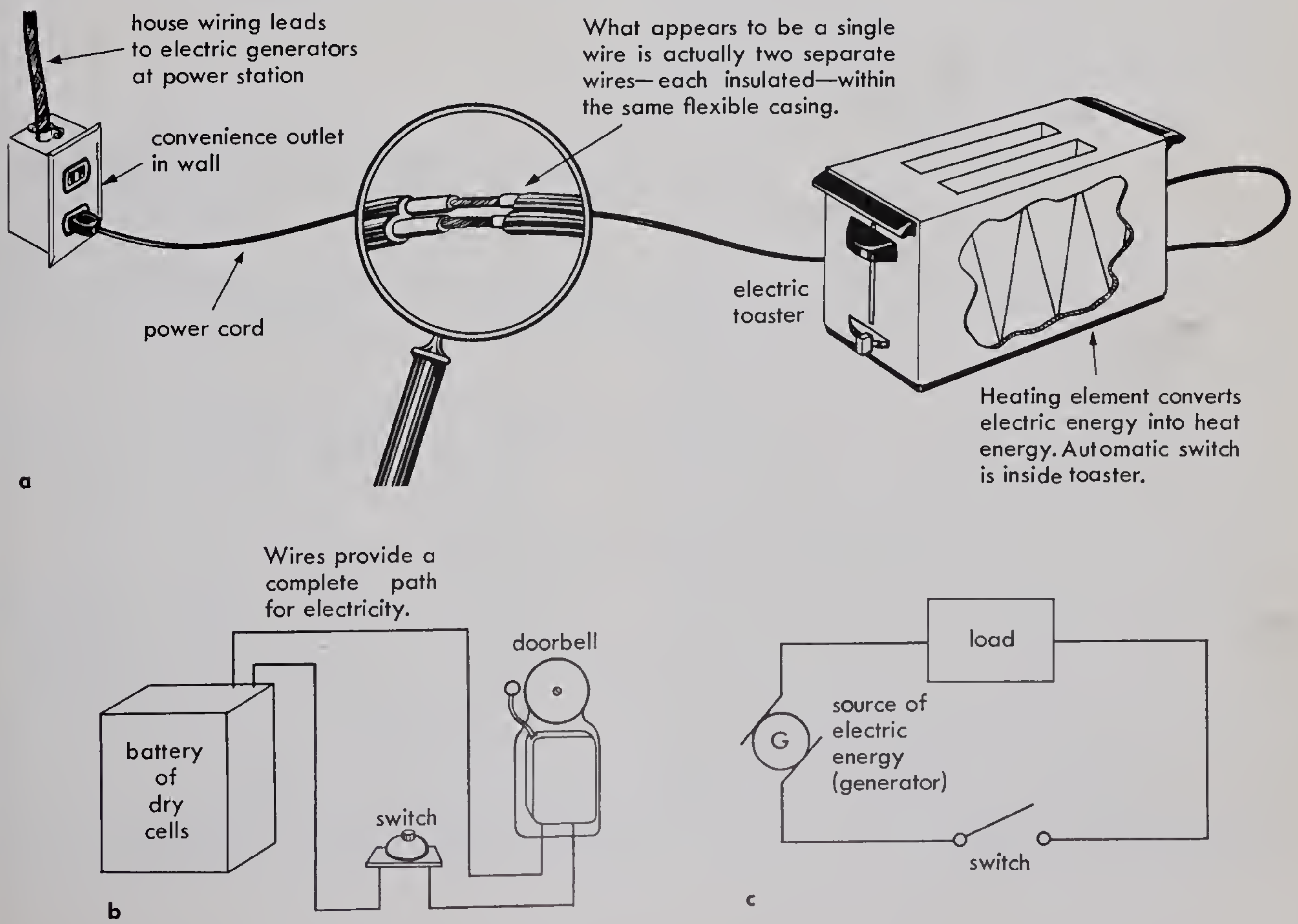
Figure 10–10b shows a simple circuit — one which might be set up in the laboratory or used to construct a doorbell system. A standard dry cell battery serves as the source of electric energy. An electric doorbell is the load. These are connected by wires. Included in the circuit is a push-button type switch.

All simple circuits have these features in common:

1. A source of electric energy.
2. A load which converts electric energy into some other energy form.
3. A complete and closed path through which electric charges can flow.

10–17 Standard symbols simplify the study of electricity. Both Fig. 10–10a and –10b show actual drawings of cells, wires, loads, etc. in a circuit. While this form of

Figure 10–10 How simple circuits are represented. **a.** A toaster is a typical electric appliance for home use. Its circuit includes a source of energy, a load, a switch, and a round-trip path for current. **b.** This simple doorbell circuit contains a source of electric energy, a load, a complete current path, and a switch. **c.** This schematic diagram uses symbols in place of the more cumbersome sketches. It makes the diagram more general; that is, a schematic diagram can represent any one of many typical circuits.


house wiring leads to electric generators at power station
convenience outlet in wall
power cord
What appears to be a single wire is actually two separate wires—each insulated—within the same flexible casing.
electric toaster
Heating element converts electric energy into heat energy. Automatic switch is inside toaster.
a
Wires provide a complete path for electricity.
doorbell
battery of dry cells
switch
b
load
G
source of electric energy (generator)
switch
c

representation is satisfactory for simple circuits, it has several disadvantages, especially for more complex arrangements of parts. The study of electricity and the understanding of electric circuits is simplified by using symbols for segments of the circuit. For example, the simple diagram of Fig. 10–10c can be modified to represent the other sketches in the same group; it is called a **schematic diagram**

Symbols are easier to prepare than photographs or sketches of parts of circuits; furthermore, they require very little space on a page. However, their principal advantage is that they are *general* in their meaning. Thus, a symbol for a simple switch can represent a toggle switch, a push-button switch, a knife switch, or a telegraph key. It can be used for a switch on a room wall, or on a flashlight case; it can be the switch which closes a circuit which fires a rocket or the switch which controls the light inside a refrigerator.

Symbols for components of electric circuits can be used in any position, since they literally have no top or bottom. Table 1 shows many of the common electrical symbols used in simple schematic diagrams.

10–18 A fuse is a special kind of switch. Electrons flowing through a wire lose a small part of their energy in the form of heat. If the current is large, the wires may become hot enough to melt or to start a fire. For this reason household circuits are protected with fuses. A **fuse** is made of a low-melting-point alloy, which melts before the other wires in the circuit become dangerously hot. When the fuse wire melts, the circuit is broken and current ceases. Common household fuses are frequently of the screw-in variety. They can be inserted into sockets mounted in the fuse panel. A cartridge fuse fits into a pair of clips. Circuits may also be protected by **circuit breakers** which use magnets or bimetallic bars to open the switch.

All household electric circuits should be protected by fuses or circuit breakers. Without them there is a good chance that an overloaded circuit may damage an appliance, scorch insulation, or even start a fire. Circuits should be equipped with fuses according to the current they can handle safely, commonly 15, 20, or 30 amperes. If a fuse has too large a current rating, it does not give protection against moderately excessive current.

Do It Now

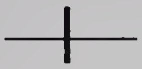
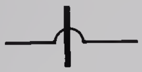
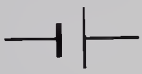
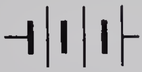
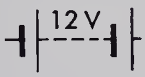
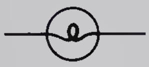
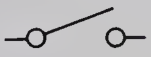
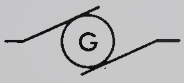
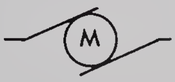
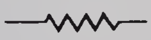
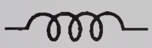
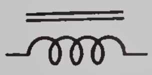
1. Check the wiring of your home to see if fuses or circuit breakers are used. In particular, determine the ampere-ratings of the fuses or circuit breakers used. Do the same for the wiring in your school building.
2. Would you expect that a fire caused by defective wiring would start in a fuse box or elsewhere in a house?

10–19 Electric energy is extremely useful to man. Have you ever wondered why electricity is such a useful form of energy, why the modern age is sometimes called "the age of electricity"? You have learned some of the reasons why this is true:

1. Electric energy can be carried in wires from one place to another — over distances from a few inches to thousands of miles.
2. Electric energy can be easily controlled by use of switches of all kinds.
3. Electric energy can be readily converted to and from many other forms, including heat, light, mechanical, and electromagnetic energy.

It is these features which make electricity so useful in modern civilization.

Table 10–1 SCHEMATIC DIAGRAMS FOR ELECTRIC CIRCUITS USE WELL-STANDARDIZED SYMBOLS. SOME OF THE MORE COMMON ONES USED IN THIS BOOK ARE SHOWN BELOW.

	Wires in electric contact
	Wires crossing, but not in electric contact
	Chemical cell — long, thin line is positive
	Battery of three chemical cells connected in series
	Battery of several chemical cells connected in series. The number of cells is not indicated, but the total number of volts is shown.
	Incandescent lamp
	Simple off–on switch — normally shown open
	Electric generator
	Electric motor
	Resistance wire or a heating coil
	Coil of wire
	Coil of wire with an iron core

Self Check

1. Why are there two separate conductors in the power cord of an appliance?
2. What are the three necessary components for a complete electric circuit?
3. In terms of these three necessary components, how does a switch control current in a circuit?
4. What are some of the advantages of using symbols and diagrams to represent electric circuits? What are some disadvantages?
5. Where did the term "fuse" originate?
6. Why is electric energy useful?

Discussion Questions

1. Identify the energy source, the load, and the complete current path for an automobile electrical system while the battery is being charged and no other energy is being released.
2. How would you design a container for an x-ray device so that no technician could remove the cover while the power is on?

Chapter Summary

Electric current in wires and loads consists of electron movement from negative to positive. The moving electrons are free electrons from the atoms of the conducting material. Free electrons move slowly, but the surge of their movement approaches the speed of light. Conductors permit easy flow of electrons; insulators do not. In liquid solutions and in gases, electric current consists of positive and negative ions moving in opposite directions in the ionized material. Electrolytes are ionized liquids. Moisture in the earth makes it a good conductor and constitutes a safety hazard.

Electric currents produce a force on each other; this force provides the basis for the definition of the unit of electric current. One ampere is the current in each of two long conductors 1 m apart which produces a force of 2×10^{-7} N per meter of conductor length. The basic unit of electric charge is the coulomb, the quantity of charge passing a given point in a circuit each second when there is a current of 1 ampere.

Every electric charge is surrounded by an electric field. An electric field produces a force on a charged object. The direction of a field is the direction of the force on a positive charge. The magnitude of the force is the product of the field strength and the quantity of charge. Energy is involved when charges move through electric fields. The potential difference between two points in a field is the energy difference as a unit of charge is moved between the two points. A volt is the potential difference between two points when 1 J of work is involved in the movement of 1 C of charge between those two points. Energies of subatomic particles can be expressed in terms of electron volts. Electric fields can be compared with gravitational fields.

Electric circuits provide a means of controlling energy. Every operating circuit contains at least three parts, a source of electric energy, a load, and a complete conducting path for current. Symbols and circuit diagrams promote easy understanding of electric circuits. An electric fuse is a switch which melts when hot and therefore automatically opens to prevent excessive current.

Vocabulary

electron current (*p. 233*)
conventional current (*p. 234*)
ionization (*p. 234*)
electrolyte (*p. 235*)
grounded wire (*p. 235*)
conductor (*p. 235*)
insulator (*p. 235*)
ampere (*p. 238*)
coulomb, microcoulomb (*p. 238*)
electric field (*p. 239*)
electric field intensity (*p. 240*)
potential difference (*p. 241*)

volt (*p. 241*)
gravitational field (*p. 242*)
electron volt (*p. 242, 243*)
electric circuit (*p. 243, 245*)
load (*p. 245*)
schematic diagram (*p. 245, 246*)
switch (*p. 246*)
fuse (*p. 246*)
circuit breaker (*p. 246*)

Problems

A **1.** How many coulombs pass a given point when a current of 5.0 A flows for 4.0 sec?

2. A 60-W electric light bulb uses a current of approximately 0.50 A. How many electrons per second pass by a point in the filament?

3. A pith ball of mass 0.10 g is free to move in an electric field whose intensity is 25 N/C. What is the acceleration of the pith ball if its charge is 30 μC?

4. A charge of 80 μC does 0.020 J of work as it jumps a spark gap. What was the potential difference across the gap?

5. What is the energy of a proton accelerated by a potential difference of 20,000 V?

6. What potential difference would be required to give an alpha particle an energy of 40,000 eV?

B **7.** Through what potential difference must an alpha particle be accelerated to give it a velocity equal to $\frac{1}{10}$ that of light? Assume that the mass of the particle does not change enough to affect the result. The mass of an alpha particle is 6.6×10^{-27} kg.

Discussion Questions

1. Many people prefer to avoid the use of the phrase "flow of current." They say this is a redundant expression. What does this mean? What is your opinion about "flow of current"?
2. Can you describe a situation where it might be useful to treat two electric fields as vector quantities and add them as vectors?
3. What is wrong with the statement: "There are 60 volts going through this load."
4. Describe the kinetic energy possessed by a 2 meV electron without using the term "electron volt".

Work on Your Own

1. Write to the Canadian Standards Association, 77 Spencer Street, Ottawa 3, for information about establishment of electrical standards.
2. Prepare a chart to compare gravitational and electric fields. For each type of field, make an entry for such things as how produced, units in which measured, kinds of things on which forces are produced, and ways of expressing energy difference between two points in the field.

CHAPTER 11

Courtesy of IBM, Inc.

These circuit boards containing resistors (the small, striped cylinders) are components of electronic computers, which use direct current. The circuit boards may be replaced easily for repair purposes or to change the characteristics of the circuit.

Direct Current

Judy first saw the wisp of smoke rising from the footlight dimmer control just as the curtain came down on the dress rehearsal of the Junior Class play. She turned off the circuit immediately, ending the danger of fire. The stage crew knew that the light dimmer controls normally became hot, but the more they thought about it, the less they understood why. As Joe pointed out, "The light and heat should come from those floodlights, not from the control box. Besides, why should the control box grow hotter while the lights are dim?"

Marilyn had an idea. "Let's call Mr. Thompson," she said. "He lives nearby and he's a physics teacher." Mr. Thompson went right over because he thought that there might be danger. He examined the dimmer control which had been smoking and shook his head sadly. "This is really ruined," he muttered. "And, say! The footlight circuit is overloaded. Those should be 100-watt bulbs, and most of them are 150's."

Two hours later everything was under control. After Marilyn had expressed wonder at his ability to fix things, Mr. Thompson commented, "I was glad to do it. I am sorry I had no time to explain how the repairs worked. If you still wish to know, why don't you take physics next year? You might enjoy your backstage work more if you knew what you were doing!"

In this chapter you will find out how energy is provided for electric circuits, what factors determine the intensity of current in a circuit, and how electric power and energy are computed.

Electric Energy Sources and Loads

11–1 Charges can be made to move in a conductor. An electric field produces a force on a charged object. By this time you are thoroughly familiar with this important principle of electricity. You know what happens to the charged pith ball in Fig. 11–1. It lies in the electric field produced by the charged objects at *A* and *B*. Since the pith ball has a negative charge, it is repelled by *A* and attracted by *B*; therefore it moves toward the right, in a direction opposite to that of the field. If the pith ball had a positive charge, it would move left, in the direction of the field.

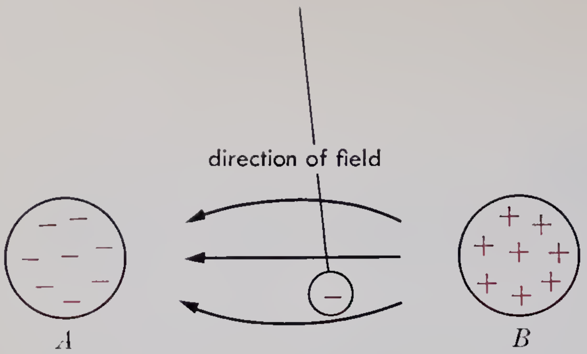


Figure 11–1 The suspended negative charge moves in a direction opposite to that of the field between A and B.

The behavior of the pith ball is almost identical whether it occurs in empty space or in air or other common gas. But what would happen if the material between A and B were a solid? What if it were a metal?

The sketch in Fig. 11–2a corresponds in general with that of Fig. 11–1. However, there are important differences in detail. For one thing, the material between A and B is no longer air, but a metal wire. For another, the suspended pith ball has been replaced by the free electrons in the wire. Since there is a potential difference between the two terminals of the cell, there is also a potential difference between A and B; consequently, there is an electric field between A and B. The field exerts a force on the electrons, causing them to move.

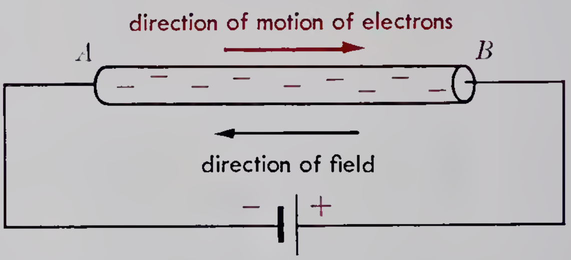
One big difference between electrons flowing in a conductor and electrons flowing in space is their velocity. Even when the potential difference between A and B is the same, as in Figs. 11–2a and 11–2b, electron movement is much slower in a conductor than in space. In a solid, electrons move but a short distance before they collide with other particles in the solid and are slowed down. That is, they are first accelerated by the field, then decelerated by collision. As a result, the average velocity of free electrons moving through a conductor is very low; that is why it is referred to as a *drift* of electrons.

As electrons are accelerated by the field between A and B in Fig. 11–2a, they acquire kinetic energy. As they collide with stationary particles, they give added energy of motion, in the form of heat, to the particles, which accounts for the heating effect of electric current in a conductor.

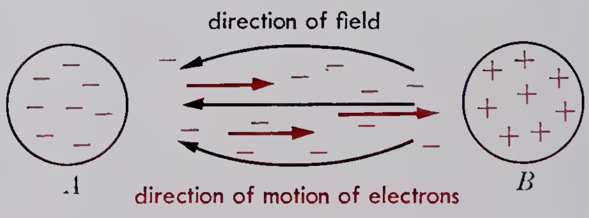
In Fig. 11–2a, the potential difference is not provided by isolated, oppositely charged objects. To sustain a current in the conductor, means must be provided to maintain the potential difference. This is almost always accomplished by the chemical energy from electric cells or by the mechanical energy which drives electric generators.

In simple circuits electron flow is in one direction only; it may fluctuate in intensity, but it does not reverse its direction; this continuous current is called **direct current (dc).**

Figure 11–2 a. Free electrons in a wire also move against the field in the wire.



b. Here electrons in space are free to move in the electric field between A and B. They move for the same reason they did in **a**, but they move much faster. Note that in all cases the electrons move in a direction opposite to that of an electric field.



Source	Volt rating
single standard-size "dry cell"	1.55 (nominally 1.5)
lead-acid storage cell	2.1 (nominally 2)
modern automobile battery	6.3 (nominally 6) or 12.6 (nominally 12)
battery for large airplane	25.2 (nominally 24 or 25)
house wiring	110–125
streetcar and electric bus	550
long-distance transmission lines	50,000–500,000
medium-sized Van de Graaff generator	0.5–2 million

Do It Now

Two identical balls roll down the incline of a pinball machine at once. One misses all the obstacles and rolls directly down to the bottom, while the other hits several pins. Which has the greater average velocity? Compare the way in which the two balls expend their potential energy. How does this situation compare with the electron movement represented in Fig. 11–2?

11–2 Electric energy sources are rated in volts. Such expressions as "12-volt batteries" or "120-volt electric supply" describe the potential difference which a source of electric energy can maintain across its terminals. Electric energy sources can be described also in terms of the rate at which they supply energy (their power) or how long they will last, but by far the most common rating is in terms of volts. **Volt rating**, as you know, indicates the energy which the electric supply can deliver to each unit of electric charge which it moves. The volt rating of some common sources of electric energy are shown above.

11–3 Electric loads are specified in volts. Most ordinary loads for electric circuits are specified in volts. However, the meaning of volt rating here is far different from its meaning when used to rate sources of electric energy. The load, of course, does not supply energy to anything. Its volt rating means that it is designed for normal operation with a given potential difference across its terminals. For example, there are miniature lamp bulbs rated at 1.2 volts, 1.5 volts, 2.5 volts, 3.8 volts, 6.3 volts, etc. Most household appliances, including lamp bulbs, are rated at 110–120 volts. Some electric stoves, clothes dryers, and water heaters are rated at 220 volts. The ratings give the potential difference required for optimum operation. A 120-volt lamp glows dimly and inefficiently when the potential difference across it is 80 volts and may not glow at all if the potential difference is much lower than that. If the potential difference is substantially above the rated value, the lamp will burn out quickly.

Do It Now

1. Examine a two-cell flashlight. What is the normal volt rating for its lamp? How does the flashlight behave with a lamp a little lower or higher than is proper?
2. If a flashlight is equipped with the wrong bulb so that it glows more brightly than normal, what happens to the life of the bulb? What happens to the life of the battery?

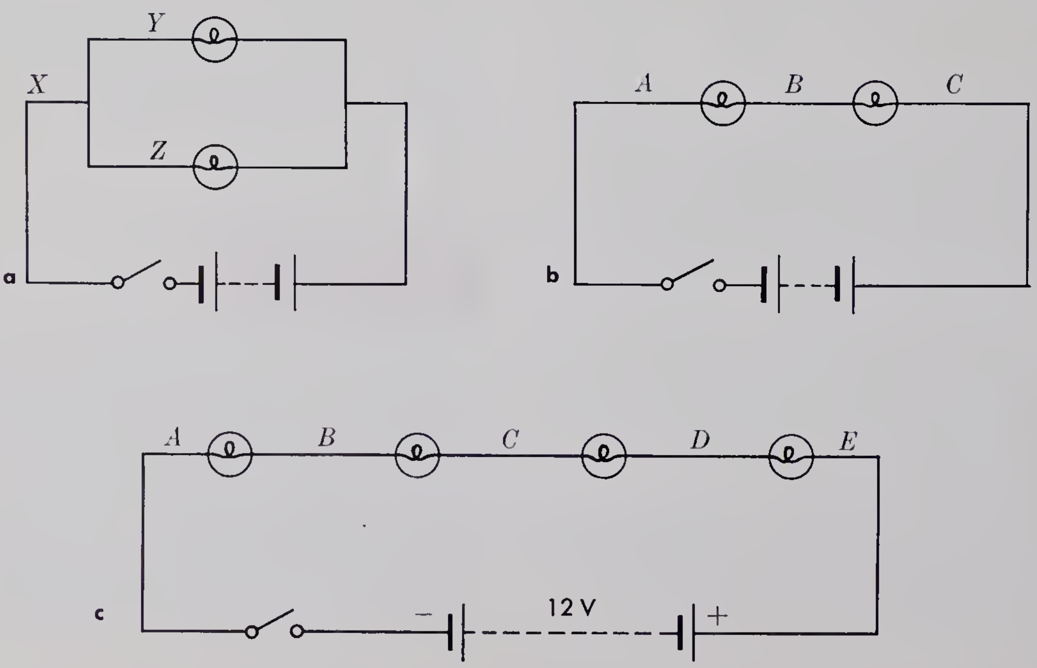
11–4 Electric loads may be connected in parallel or in series. It is evident that a 12-volt lamp operates normally from a 12-volt battery. But how can you operate two or more such lamps from this source of energy? And how can you use lamps with lower volt ratings with a 12-volt source? These problems can be solved by using series or parallel circuits. Figure 11–3 shows a simple circuit consisting of a battery, a switch, and two lamps. The circuit is arranged first with the lamps in parallel (Fig. 11–3a) with each other and then with the lamps in series with each other (Fig. 11–3b).

In the **parallel** arrangement, the current divides and goes through each lamp in equal quantities if the lamps are identical. If one lamp is removed, the circuit is still complete; but only half as much current remains because half of the conductive path has been removed. If a 12-volt battery is the source of electric energy, each parallel-connected lamp should be a 12-volt unit, to match the potential difference of the energy supply. If the lamps are alike, each glows with equal brilliance. Two parallel lamps will discharge the battery in half as much time as will a single lamp. In Fig. 11–3a, a switch at point *X* would control all the lights in the circuit, while a switch at *Y* would control only the lamp in that particular branch of the circuit.

In the **series** arrangement, the same current exists in each lamp, for every electron which goes from *A* to *B* also must go from *B* to *C*. Since no electrons are added or lost and since they do not "pile up" in the circuit, the number flowing through *AB* in a given time must be the same as the number flowing through *BC*. Hence, the flow of charge per unit of time, the electric current, is the same in all portions of a series circuit. In this circuit, if either lamp is removed from its socket, the circuit no longer is complete and no current flows.

To operate four identical lamps in a series circuit containing a 12-volt battery, you must select lamps whose individual volt ratings add up to approximately 12 volts.

Figure 11–3 Here the same components are arranged (**a**) in parallel and (**b**) in series. In parallel each lamp has the same potential difference across its terminals. In series each lamp has the same current. **c.** Here a 12-V energy source is used to move electrons through four identical lamps connected in series.



Therefore each lamp should be rated at 3 volts. You can understand this by referring to the circuit analysis in Fig. 11–3c. The potential difference between *A* and *B* is 3 volts, likewise the one from *B* to *C*, etc. *A* is negative with respect to *B*, *B* is negative with respect to *C*, and so on. Accordingly, the potential difference is such that *A* is 6 volts more negative than *C*, and 12 volts more negative than *E*. A switch in series with this circuit controls all the lamps, since a break at any point in the conductive path makes the entire circuit incomplete and stops the current.

Only a few examples of series-connected loads are in ordinary use. One is the arrangement of small Christmas-tree lamps on a single cord. A common variety of these ornaments has seven or eight 15-volt lamps in a series, making a load whose total volt rating is approximately equal to that of the electric energy supply of a typical home. Because the lamps are in a series, all go out when one fails. Other series-connected loads are the heaters of the vacuum tubes in many small radio receivers. If one of the heaters fails, none of the tubes glows.

Do It Now

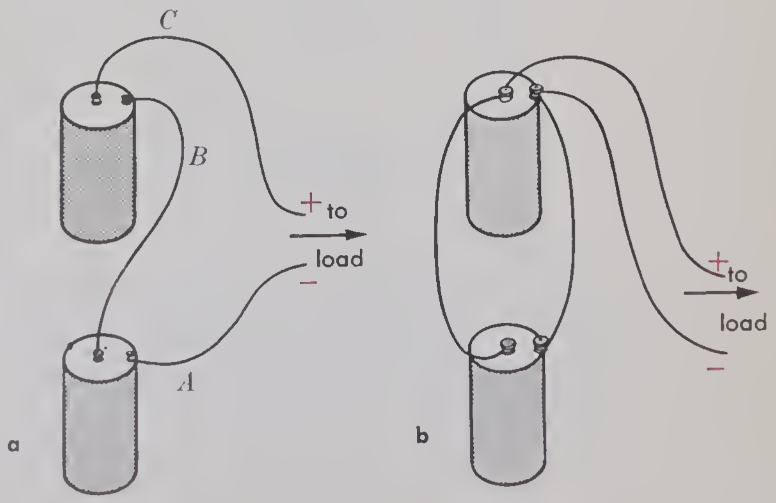
If you have one 3-volt lamp which uses 2 amperes, and another 3-volt lamp which uses 1 ampere, would you connect them in series using a 6-volt battery, or in parallel using a 3-volt battery? Why?

11–5 Electric energy sources may be connected in parallel or in series. Not only electric loads, but electric cells may be connected in parallel or in series. Series connections of cells, as in Fig. 11–4a, provide a greater total potential difference than that available from a single cell. The negative terminal of one cell is connected to the positive terminal of the next. The potential differences of the cells in a series arrangement add up to the potential difference of the battery.

Typical flashlight batteries are made up of cells stacked in series inside the case. Since the metal bottom of such a cell is the negative terminal while the brass cap on the top is the positive terminal, this amounts to connecting the cells in series. The cells of an automobile storage battery are also connected in series. Each lead-acid chemical cell has a rating of 2.1 volts. Hence, the six-cell battery used in most automobiles has a 12.6-volt rating. In common practice, such batteries are referred to as 12-volt batteries.

Electric cells sometimes are connected in parallel. A battery made of any number of similar cells connected in parallel has the volt rating of a single cell. Its action is similar to that of a single cell with larger plates and more chemicals. Doorbell batteries often are made of three or four parallel-connected dry cells. The rating of such a battery is 1.5 volts, but it will operate for three or four times as long as a single cell. Figure 11–4b shows such a connection.

Figure 11–4 **a.** These two dry cells are connected in series. The center terminal of each is positive with respect to the side terminal. *B* is 1.5 V more positive than *A*, and *C* is 1.5 V more positive than *B*. From this it follows that *C* is 3 V more positive than *A*. **b.** The same two cells connected in parallel.



Self Check

✓ **1.** When will charges move in conductors?

2. Why do wires heat up when they conduct electric current?

3. How is a potential difference maintained in a conductor?

4. What is meant by the term "direct current"?

5. What is the difference in meaning when a battery is described as having a volt rating of 24 V and when a motor is described as having a volt rating of 24 V?

6. What is the volt rating of most household appliances?

7. What is the volt rating of a dry cell? of a storage cell?

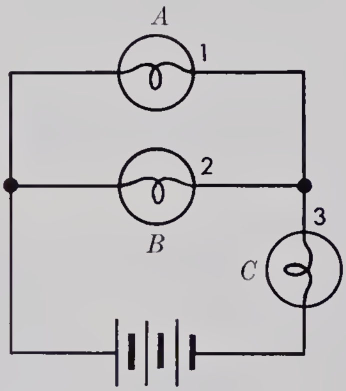
8. A flashlight bulb is rated at 3.8 V. What happens if you operate it at 2.5 V?

9. What happens if you operate a 3.8-V flashlight bulb at 6.3 V?

10. Two light bulbs, *A* and *B*, are connected in series with each other and then connected to a battery which consists of four cells in series. Diagram the circuit.

11. If the cells of Question 10 are lead-acid storage cells, what is the volt rating of the battery?

12. In the circuit shown, which lights will go out if a switch at *1* is opened? If a switch at *2* is opened? If a switch at *3* is opened?



13. Considering the four parts of the circuit of Question 12 to be the three lamps and the battery, which two are certain to have the same current?

14. Which two parts of the circuit in Question 12 are certain to have the same potential difference between their terminals?

Problems

Ⓐ **1.** A typical flashlight cell normally maintains a potential difference of about 1.25 V across its terminals. How many cells in series are needed to operate a flashlight lamp rated at 6.3 V?

✓ **2.** If you have one 6-V lamp using 5 A and another one using 8 A, how would you design a circuit using eight 1.5-V dry cells so that each lamp would burn with normal brilliance?

✓ **3.** A hot-rod enthusiast is converting an old car with a 6-V electrical system into one with a 12-V system. In the interest of economy, how can he make effective use of his old 6-V lamps?

✓ **4.** Draw a diagram for a circuit using five lamps connected in parallel. Provide one switch which controls only lamp No. 1, a second switch which controls lamps No. 2, No. 3, and No. 4, and a third switch which controls all five lamps.

Discussion Questions

1. What would happen if the electric field in Fig. 11–2a were in an insulating material rather than in a conductor? Is it accurate to say that an electric field could exist in such a material? Explain the behavior of electrons in the insulator.

2. How would a flashlight operate if you inserted the cells with their brass tips touching? How would you interpret this, knowing that a series-connected battery maintains a potential difference equal to the sum of those of its individual cells?

3. What would be the result if you connected a 1.5-V dry cell and a 2-V storage cell in parallel with their positive terminals together?

Electrical Resistance

11–6 Some materials oppose the flow of electrons more than others. It is evident that the volt rating — the potential difference maintained at the terminals — of a source of electric energy influences the magnitude of current in a circuit. This cannot be the only determining factor, or all circuits containing 12-volt batteries would have identical currents. Another determining factor is the nature of the connecting wires and the loads which make up the circuit.

As you have learned, some materials do not obstruct the flow of free electrons as much as others. In electricity the property of a substance that opposes, or limits, the flow of electric charge through it is called its **resistance.** The resistance of a part of a circuit depends on the nature of the material of which it is made, its physical dimensions, and its temperature. A **resistor** is a part or component of a circuit which is intentionally designed to possess resistance.

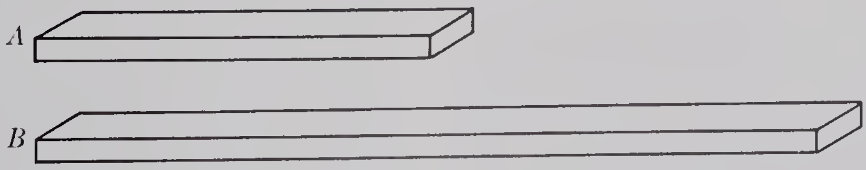
Oddly enough, the terms *resistor* and *conductor* often are used to describe the same thing! Usually when a part of a circuit is used to provide a path for the movement of charge, it is called a **conductor.** Thus connecting wires are conductors; they are designed to have low resistance, although it is never zero. On the other hand, when resistance is inserted in a circuit deliberately to limit current, or for some similar purpose, the specific part is called a resistor.

Do It Now

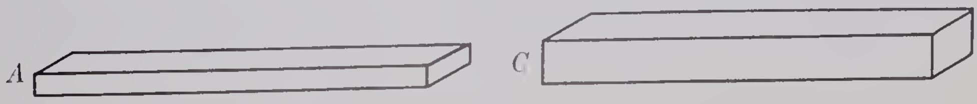
Resistance is the property of an object which opposes electron flow; conductance is the property which permits electron flow. Obviously, these two words are just opposite ways of expressing the same idea. Examine the definition of a resistor above, and make a corresponding definition of a conductor.

11–7 Physical dimensions affect resistance. To understand the effects of physical size on resistance, look at Fig. 11–5a. The two conductors have identical material and cross-sectional area; they differ only in length. Conductor *B*, which is twice as long as *A*, acts just like two lengths of conductor *A* connected end to end. Therefore, the resistance of conductor *B* is twice that of conductor *A*. In general, other things being equal, the resistance of a conductor is directly proportional to its length.

Figure 11–5 a. Conductor B is the same as Conductor A, except that it is twice as long. For this reason, electrons encounter twice as much resistance going through B as going through A. This shows that resistance is directly proportional to length.



b. Conductor C is the same as Conductor A, except that C has twice the cross-sectional area of A. For this reason, C has twice as many electrons per unit length and therefore has only half as much resistance to electric current as A has.



Conductors A and C in Fig. 11–5b are of identical material and length, but C has a cross-sectional area twice as great as that of A. Conductor C has twice as many free electrons per unit length as does A, so the total resistance of C is one-half that of A. In general, other things being equal, the resistance of a conductor is inversely proportional to its cross-sectional area.

Do It Now

Electric currents are often compared to water currents, but the analogy is misleading in many respects. A better comparison, although not a perfect one, is between a flow of electrons in a conductor and a flow of automobiles on a highway. Describe a traffic situation which illustrates how current (of cars) depends on the cross-sectional area of the "conductor."

11–8 Temperature affects resistance. In almost all materials, resistance increases with the temperature, and this change in resistance is very nearly proportional to the number of degrees in change of temperature. The resistance of an object approaches zero as its temperature approaches absolute zero. Carbon, one of the interesting exceptions to this relationship, decreases in resistance when the temperature increases.

The variation of resistance with temperature changes is a nuisance in electric measuring instruments. In an effort to overcome this, scientists have developed conductors whose variation in resistance with temperature changes is negligible. For example, manganin, an alloy of copper, manganese, and nickel, changes resistance less than 1 part per 100,000 for each degree Celsius of temperature change.

11–9 Ohm's law relates current, potential difference, and resistance. Since the electric resistance in a circuit is so important in determining the intensity of electron flow, it is clear that resistance is very important in the quantitative aspects of electricity. It must have been realized very early that, other things being equal, an increase of resistance in a circuit was accompanied by a decrease in current. A precise statement of this relationship had to await the development of reasonably reliable measuring instruments. In the 1820's Georg Simon Ohm, a German schoolteacher, found that the current in a circuit was directly proportional to the potential difference producing the current, and inversely proportional to the resistance limiting the current. Expressed mathematically:

$$I \propto \frac{V}{R}$$

where I is current, V is potential difference, and R is resistance.

This basic relationship bears the name of the man most responsible for its formulation; it is called **Ohm's law**.

11–10 The ohm is a unit of electrical resistance. Replace the proportionality sign in Ohm's law by an equals sign:

$$I = \frac{V}{R}$$

Now solve for R:

$$R = \frac{V}{I}$$

In this form Ohm's law defines the unit of electrical resistance. The resistance of a conductor is 1 **ohm** (Ω, the Greek letter, *omega*) if it permits a current of 1 ampere to exist when a potential difference of 1 volt is maintained across the resistance.

$$R \text{ (in ohms)} = \frac{V \text{ (in volts)}}{I \text{ (in amperes)}}$$

Therefore, 1 ohm = 1 volt/ampere.

11–11 Ohm's law has many practical applications. No mathematical relationship is employed more often in electric circuits than Ohm's law. Because it relates three fundamental concepts in electricity, it helps physicists and electricians solve many problems.

Do It Now

Conductance is the opposite of resistance. Mathematically, one is the reciprocal of the other. The unit of conductance, appropriately enough, is the mho, ohm spelled backwards! What is the conductance of a 20-ohm resistor? Of a 0.1-ohm resistor? Of a 1-ohm resistor?

11–12 Ohm's law has limitations. In spite of the usefulness of Ohm's law, it has definite limitations. Among these are:

1. Ohm's law applies only to solids, not to ionized liquids and gases.
2. Ohm's law must take into consideration any temperature changes. This is particularly important since all resistors grow warmer when electrons flow through them.
3. Ohm's law must be modified for use in alternating-current circuits.
4. Some combinations of materials conduct charges better in one direction than in the other.

The limitations of Ohm's law are well explained by advanced theories of the structure of matter. The law, like Boyle's law should be regarded as an empirical statement whose value is enhanced when its limitations are recognized.

11–13 Ohm's law is related to rules of personal safety. You probably have felt an electric shock. Fortunately, these rarely are strong enough to cause pain. However, electric energy, even at low potential differences, can be dangerous.

An electric potential difference itself does no harm, except at hundreds of thousands of volts. The pain and the danger are due to the current which the potential difference produces in the body. A small fraction of an ampere can kill a person if the current is in vital organs. How much potential difference can produce lethal current? This can be understood in terms of Ohm's law and the resistance of the body.

The degree to which the body conducts electric charge depends on the body's condition. Internal flesh is very moist, an electrolyte, and a good conductor of electricity, while the dry outer layers of skin are fair insulators. As a rule, there is enough resistance on your dry skin to limit current to a safe intensity if the potential difference is not too great. With normally dry skin, you cannot even feel 12 volts, and a potential difference of twice that scarcely tingles. But if the skin is moist, even such a low potential difference can produce a nasty shock.

Every year many persons in North America are killed by 120-volt electric circuits. Usually this is caused by carelessness or ignorance. Often these victims are standing in a bathtub or with wet shoes on a concrete floor or are holding a faucet with wet hands, when the accident occurs. One man was killed by a 32-volt storage battery while standing knee-deep in water and grasping a "hot" wire firmly with both hands!

Self Check

1. What is the relation between current, potential difference, and resistance in a circuit?
2. What factors affect the electric resistance of an object?
3. How does Ohm's law provide a mathematical definition for the unit of electric resistance?

4. Why is it useful to know the limitations of Ohm's law? What are they?
5. The resistance of a wire is 12 Ω. What would be the resistance of an identical wire with a diameter three times as great?
6. The resistance of a wire is 12 Ω. What would be the resistance of an identical wire, three times as long?
7. A current of 3 amperes flows when a resistor is connected across a 12-volt battery. What is the resistance of this resistor?
8. An electric toaster has a resistance of 12 Ω when it is hot. What current will it permit when connected to a 120-volt line?
9. When the toaster in Question 8 is first turned on, will it permit more, less, or the same current as when it is hot?

Problems

Make a diagram to illustrate the problem whenever this is helpful.

A 1. The resistance of a wire is 10 Ω. What is the resistance of a wire of identical material that is (a) one-half as long; (b) one-quarter as great in diameter; (c) twice as long, with one-half of the diameter?

2. A simple circuit operating from a 24-V battery contains a total of 120 Ω resistance. What is the current?

3. It is desired to have a current of 8.0 A in a load whose resistance is 50 Ω. What potential difference is required?

4. A bathroom heater draws 15 A when operating from a 120-V line. What is its resistance while operating?

5. One type of flashlight dry cell is tested at the sales counter by connecting a heavy wire momentarily across its terminals and measuring the current. If the current is 7 A, the cell is considered to be in perfect shape. If these cells have a volt rating of 1.55 V, what is the internal resistance of such a cell?

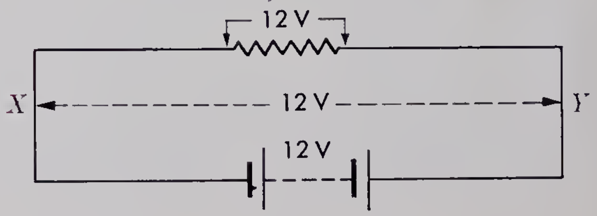
Discussion Questions

1. A section of moist earth an inch in diameter and a yard long has a resistance of a few ohms. Why, then, is the resistance between two pipes driven into the ground a mile apart extremely small?
2. The resistance of a certain resistor varies greatly with change in temperature. Design a circuit that could use such a resistor as a temperature-measuring device. Suggest one or two useful applications for such an arrangement.

Resistors in Series and in Parallel

11–14 Resistors are sometimes connected in series. Students often think that potential difference exists only across the terminals of a source of electric energy. The simple circuit of Fig. 11–6 shows that this is not the case. Here the battery gives energy to a charge carried across its potential difference, just as you might give energy to a rock by carrying it uphill. Then the charge travels "downhill" through the resistor, converting the energy to heat. If a charge of 1 C goes "uphill" through a 12-V potential difference in the battery, it gains 12 J of energy. Then it goes down through a 12-V potential difference in the resistor, giving up 12 J of energy.

Figure 11–6 Here it is evident that the potential difference across the load is the same as the potential difference maintained by the energy source.



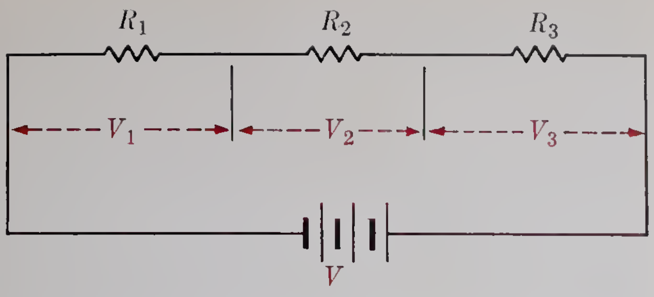


Figure 11–7 This diagram shows a circuit with resistors in series.

The situation in Fig. 11–7 is somewhat more complex. Here the battery pushes the charge "uphill" through a potential difference of V volts. Then the charge comes "downhill" in three stages, first through R_1, then through R_2, and finally through R_3. If you knew the current in the circuit, you could use Ohm's law to calculate the downhill potential difference across each of the resistors. The same current exists in each resistor, since there is no other possible path. Therefore the three potential differences are IR_1, IR_2, and IR_3. The potential difference across a resistor frequently is referred to as the IR potential difference, or the ***IR* drop**.

The total IR drop across the three resistors of Fig. 11–7 must be V volts. Expressed mathematically:

$$V = IR_1 + IR_2 + IR_3$$

If R_T is the total resistance of the group of resistors, then V also is equal to IR_T. Therefore:

$$IR_T = IR_1 + IR_2 + IR_3$$

Divide by I:

$$R_T = R_1 + R_2 + R_3$$

From this reasoning, you can see that when resistors are connected in series, the total resistance is equal to the sum of the individual resistances.

11–15 Resistors are sometimes connected in parallel. Figure 11–8 illustrates a circuit with resistors in parallel. Here the total current from the battery splits among the three resistor paths. Think of a charge that travels through R_1. It went up V volts when it passed through the battery. Therefore it must go down V volts in R_1, since it does not pass through any other resistor on its way back to the battery. By a similar line of reasoning, the potential drop across R_2 and R_3 must also be V volts. Whenever resistors are connected in parallel, the potential drop across each resistor is the same.

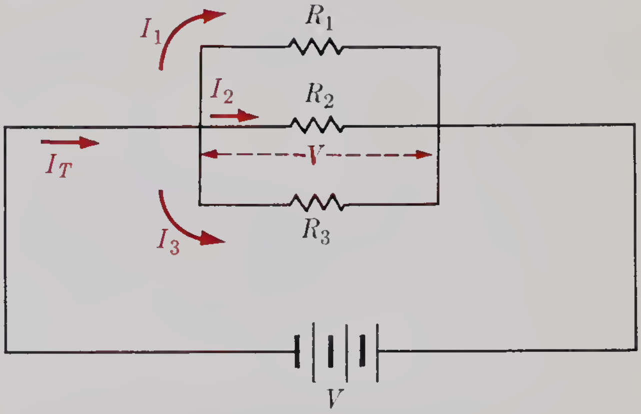


Figure 11–8 This diagram shows a circuit with resistors in parallel.

Ohm's law can be used to find the current in each resistor:

$$I_1 = \frac{V}{R_1}; \quad I_2 = \frac{V}{R_2}; \quad I_3 = \frac{V}{R_3}$$

The total current in the wire leading to the parallel group must be the sum of the three:

$$I_T = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

But $I_T = \frac{V}{R_T}$. Substituting:

$$\frac{V}{R_T} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

Divide both sides by *V*:

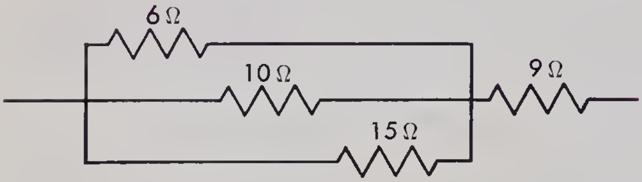
$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

This equation is used to find the total resistance of a group of resistors connected in parallel, as shown in Example 1.

EXAMPLE 1

What is the resistance of the network shown?

Given: Four resistors connected as shown.



To find: R_{total}

Solution: For the parallel part of the network:

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$= \frac{1}{6\Omega} + \frac{1}{10\Omega} + \frac{1}{15\Omega}$$

$$= \frac{10}{60\Omega} + \frac{6}{60\Omega} + \frac{4}{60\Omega}$$

$$= \frac{20}{60\Omega}$$

$$R_p = \frac{60\Omega}{20} = 3\Omega$$

Hence the parallel network is equivalent to a single resistor of 3Ω. This is in series with the 9Ω-resistor:

$$R_{\text{total}} = R_1 + R_2$$

$$= 3\Omega + 9\Omega = 12\Omega\text{, Answer}$$

The total resistance of the parallel network is less than that of any of the resistors which form it, because three conductors in parallel, as in the example, provide three paths for the current. The effect is the same as if you supplied a wire with a greater cross-sectional area. Since resistance is reduced when the cross-sectional area of a wire increases, the total resistance of the parallel group should be less than that of any of its individual resistors.

11–16 The polarity of an *IR* drop can be determined. When computing the *IR* drop across a circuit component, it is often useful to know which end of the component is negative with respect to the other end. You can understand this through a simple thought experiment. First cover Fig. 11–9b and look only at Fig. 11–9a. Here is a resistor whose current is due to the energy source — possibly a single cell — in the black box. A suitable instrument shows that the left end of the resistor is negative with respect to the other. Surely, then, the left terminal of the black box also is negative with respect to the right terminal. The contents of the black box must be as shown in Fig. 11–9b. Electrons flow in a clockwise

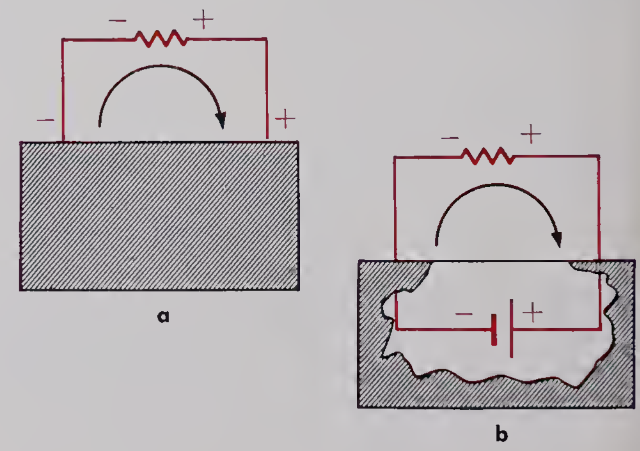


Figure 11–9 These figures accompany the thought experiment of Section 11–16. They help explain the fact that the end of a load (or a part of a load) at which electrons enter is negative with respect to the end from which electrons leave.

direction in this circuit. Since they are repelled by the negative terminal of the cell, they go through the load and back to the cell's positive terminal.

Now you can see the relationship between the direction of electron flow and the polarity of the *IR* drop. This polarity in any portion of a load is such that the point where electrons enter the load component is negative with respect to the point where electrons leave it.

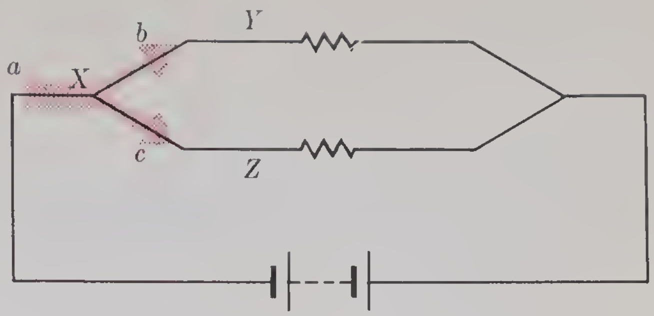


Figure 11–10 Current *a* splits to form current *b* and current *c*. This illustrates Kirchhoff's first rule: At any point in a circuit the algebraic sum of the currents entering and leaving the point is zero.

11–17 Kirchhoff's rules are used to analyze circuits. Study Fig. 11–10. Some of the electrons approaching junction *X* go off toward *Y*, and some go toward Z. Since no electrons are added or lost at *X*, it follows that current *a* equals the total of current *b* and current *c*. That is, the total current entering a point in a circuit equals the total current leaving that point. Or, at any point in a circuit, the algebraic sum of current approaching and leaving is zero. This important relationship is known as **Kirchhoff's first rule.** Kirchhoff was a German pioneer of electric circuit analysis in the mid-1800's.

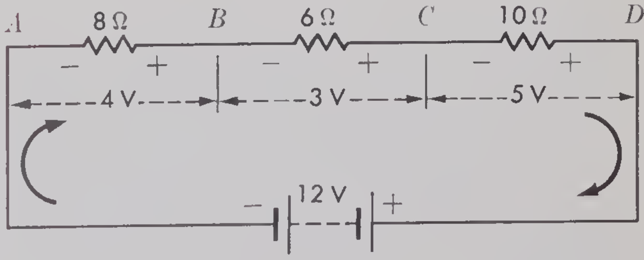
This rule assumes that the currents involved have been given an algebraic sign corresponding to their direction. Thus, current toward the point in question might be considered as positive, and current away from the point, negative.

Kirchhoff's second rule is illustrated by Fig. 11–11 which is similar to Fig. 11–7. Polarity symbols have been added to the three parts of the load. The + and − signs, side by side at points *B* and *C*, indicate that point *B* is + with respect to *A*, but − with respect to *C*. This is much like saying that a table top is higher than the floor, and at the same time lower than the ceiling.

Pretend to travel clockwise around the circuit. If a negative-to-positive potential difference is considered forward, each of the potential differences in the resistors is forward. Similarly, the potential difference of the battery is backward. Notice that the sum of the forward potential differences (4 volts, 3 volts, and 5 volts) equals the total backward potential difference. If the forward potential differences are called positive; and the backward ones, negative, then: In any closed loop of a circuit, the algebraic sum of the potential differences is zero, or, Σ potential differences = 0.

The situation in the circuit in Fig. 11–11 can also be understood in terms of electric energy. Each coulomb of charge which the 12-volt battery delivers has 12 J of energy. As each coulomb passes through each of the load's three resistors, it gives up 4 J, 3 J, and 5 J of energy, respectively.

Figure 11–11 This diagram illustrates Kirchhoff's second rule: In a closed loop of a circuit the algebraic sum of the potential differences is zero. The solid arrows indicate direction of electron flow.



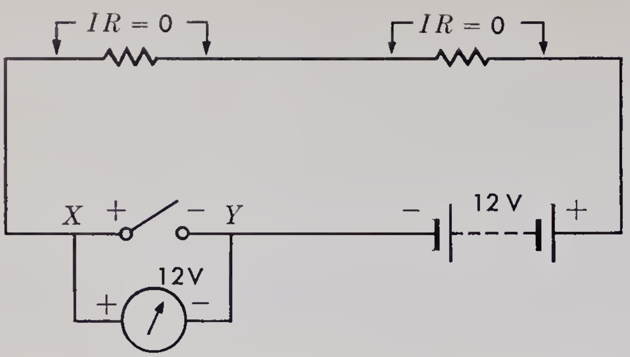


Figure 11–12 This circuit shows how Kirchhoff's second rule applies to an open circuit as well as to a closed loop. The voltmeter at lower left indicates that point X is 12 V positive with respect to point Y.

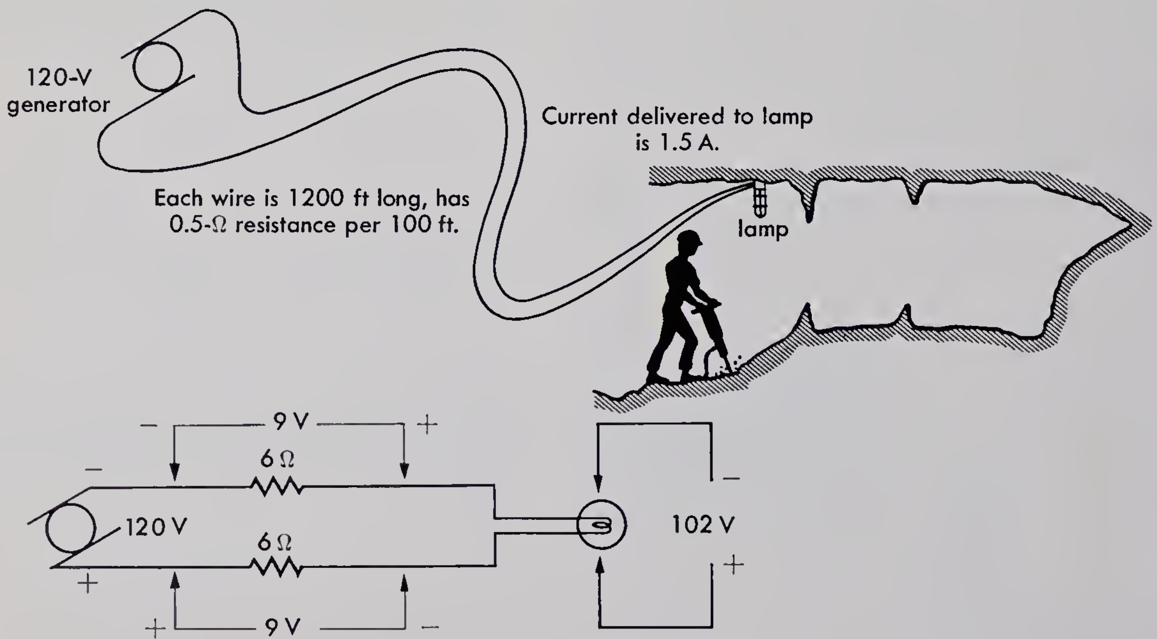
Even a nonoperating circuit (Fig. 11–12) is subject to analysis by Kirchhoff's second rule. Because no current exists in the resistors, the IR drop in them is zero. Since Kirchhoff's rule holds here, the potential difference across the open switch must be 12 volts, with the polarity as indicated. A voltmeter placed across the switch terminal would show that this is indeed the case.

11–18 The resistance of circuit wiring must be considered. In the circuits considered so far, the resistance of the connecting wires themselves has been assumed to be zero. In circuits which cover small distances the wire, or "line," resistance usually is negligible. This is not the case, however, in fairly large-scale circuits.

Suppose a 120-volt generator is used to light a lamp that is deep in a mine 1200 ft away. If each conductor has a resistance of 0.5 Ω/100 ft, then each conductor has a total resistance of 6 Ω and the equivalent circuit is as shown in Fig. 11–13. If the current is 1.5 amperes, then there is a 9-volt IR drop, or line drop, in each conductor, as in the diagram. As a result, the potential difference across the lamp terminals is 120 volts − (9 volts × 2) = 102 volts. As a result the lamp glows, but only dimly.

While the example above is a somewhat extreme case, that in Fig. 11–14 is very common. The house wiring from the community electric supply to the appliance is of No. 14 copper wire and is 80 ft long. The

Figure 11–13 A complete analysis of a circuit must include the resistance of the wires. Sometimes this can be ignored. In long circuits, such as that illustrated below, the IR drop in the leads may be great enough to produce noticeable, even troublesome, effects.


120-V generator
Current delivered to lamp is 1.5 A.
Each wire is 1200 ft long, has 0.5-Ω resistance per 100 ft.
lamp
−
9 V
+
6 Ω
−
120 V
6 Ω
+
+
9 V
−
−
102 V
+

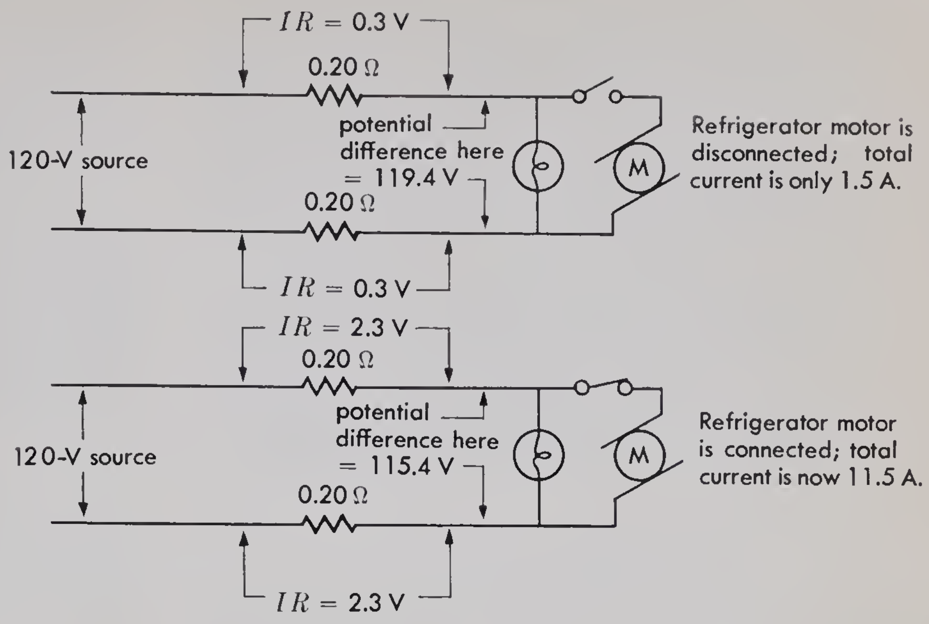

$IR = 0.3$ V
0.20 Ω
120-V source
potential difference here = 119.4 V
0.20 Ω
$IR = 0.3$ V
M
Refrigerator motor is disconnected; total current is only 1.5 A.
$IR = 2.3$ V
0.20 Ω
120-V source
potential difference here = 115.4 V
0.20 Ω
$IR = 2.3$ V
M
Refrigerator motor is connected; total current is now 11.5 A.

Figure 11–14 These diagrams help to explain how the IR drop in a supply line may be noticeable when the current drawn is relatively large.

resistance of such wire is about 0.0025 Ω/ft, which is about 0.20 Ω in each conductor. If the lamp draws 1.5 amperes, the potential difference over the length of each 80-ft line is 0.3 volts. Therefore, the potential difference across the kitchen lamp is not 120.0 volts but 120.0 volts − 0.6 volts = 119.4 volts. The fall of potential due to line drop in this case is so small as to be unnoticeable and unimportant.

But now suppose the refrigerator motor starts. For the first half second or so, while it is picking up speed, it may draw as much as 10.0 amperes. During that time, the total current in the line is 11.5 amperes, and the total line drop is $IR = 11.5 \times 0.20 \times 2 = 4.6$ volts. While the motor is starting, the potential difference supplied to the motor and lamp is only 115.4 volts. This loss in potential difference is large enough to produce a noticeable dimming of the kitchen light momentarily. As soon as the motor is at full speed, it draws less current, and the light glows brightly again.

For a similar reason the potential difference available for appliances is often reduced at night, when current drawn is large and IR drop in the line is relatively large.

11–19 The internal resistance of the energy source is important. Up to this point it has been assumed that a chemical cell maintains a potential difference across its terminals without affecting the circuit in any other way. In particular, no mention has been made of any resistance inside the cell itself. Actually, of course, electric charges do flow within the solids and liquids of the cell. These materials offer substantial resistance to current, particularly in small cells. The behavior of circuits can be understood well only if the internal resistance of chemical-electric cells and mechanical-electric generators is taken into account.

Figure 11–15 suggests a useful way of thinking of the internal resistance of a dry cell — as a small but definite resistance

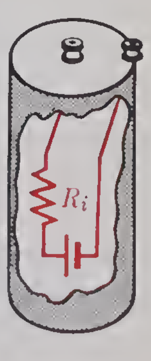


Figure 11–15 Every energy source has internal resistance. It is useful to think of the internal resistance of a cell, as shown here, as a small resistor R_i which cannot be removed.

which cannot be removed. The internal resistance in generators and lead-acid storage cells is extremely small — often negligible. In new dry cells it may be a few hundredths of an ohm. As a dry cell is used, its internal resistance increases and approaches a large fraction of an ohm by the time the cell is discarded.

The effect produced by the internal resistance of a cell is illustrated in the circuit in Fig. 11–16. Note that the total resistance — internal plus external — of the circuit is 3.02 Ω. From Ohm's law, the current in the circuit is:

$$I = V/R = 1.50\text{ V}/3.02\Omega = 0.497\text{ A}$$

The potential difference across the internal resistance of the cell is:

$$\begin{aligned} V &= IR = 0.497\text{ A} \times 0.020\Omega \\ &= 0.0099\text{ V} = 0.01\text{ V (approx.)} \end{aligned}$$

According to Kirchhoff's second rule, the sum of the potential differences around a closed loop, in this case the entire circuit, is zero. That is:

$$\left\{\begin{matrix}\text{potential difference produced} \\ \text{by chemical action within cell}\end{matrix}\right\} - \left\{\begin{matrix}\text{potential difference across} \\ \text{internal resistance of cell}\end{matrix}\right\} - \text{potential difference across load} = 0$$

Notice that the potential difference generated by chemical action is considered as opposite to the potential differences across internal and external resistances. Substituting known quantities into this relation:

$$1.50\text{ V} - 0.01\text{ V} - \text{potential difference across load} = 0$$

From this you can see that the potential difference maintained across the load terminals is actually only 1.49 volts. Furthermore, this is also the potential difference maintained across the cell's terminals while it is delivering this quantity of current. If the current drain is larger or the internal resistance of the cell greater, the result is more pronounced. See Example 2.

EXAMPLE 2

A cell whose chemical action provides a potential difference of 1.10 V has an internal resistance of 0.15Ω. What is the potential difference across the internal resistance when the current is 3.0 A? What potential difference does the cell maintain across its terminals under these conditions?

Given: $V = 1.10\text{ V}$ $R = 0.15\Omega$
$I = 3.0\text{ A}$

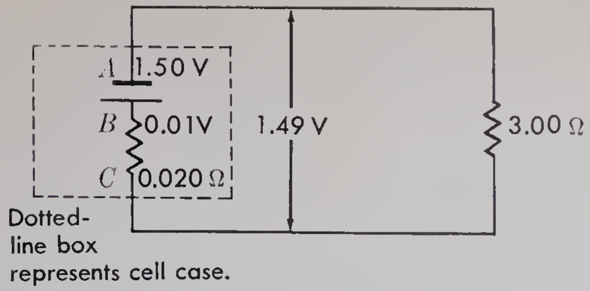
To find: V_i and V_{term}

Solution:

$$\begin{aligned} V_i &= IR \\ &= 3.0\text{ A} \times 0.15\Omega \\ &= 0.45\text{ V, Answer} \\ V_{\text{term}} &= V_{\text{emf}} - V_i \\ &= 1.10\text{ V} - 0.45\text{ V} \\ &= 0.65\text{ V, Answer} \end{aligned}$$

11–20 Electromotive force is closely related to potential difference. If a 1-C charge goes through a load across which is a potential difference of 3 volts, the charge loses 3 J of energy. If it goes through a 3-volt battery, it gains 3 J of energy. Both the load and the battery have 3-volt potential differences, but the load takes energy from the charge, while the battery gives it energy.

Each of these uses of the concept of potential difference is correct. A closely related term often confused with potential difference when speaking of energy sources is the **electromotive force (emf)** of a cell or generator. This is the potential difference actually produced by the chemical or mechanical action of the cell or generator. In Fig. 11–16, the emf of the cell is the potential difference from *A* to *B*, which does not include the cell's internal resistance. When a cell is in use, the potential difference (not the emf) maintained across its terminals is equal to the emf due to



Dotted-line box represents cell case.

Figure 11–16 When current exists in the cell of this circuit, the internal *IR* drop is about 0.01 V. Since the emf of the cell is 1.50 V, the potential difference that it maintains under this load condition is 1.49 V.

chemical action minus the *IR* drop across the internal resistance of the cell (between *B* and *C* in Fig. 11–16). Using Kirchhoff's second rule:

$$\text{emf} - IR_{\text{internal}} - IR_{\text{external}} = 0$$

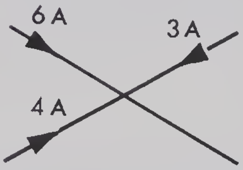
The potential difference at the terminals of a cell equals the cell's emf only if the internal resistance is zero or if the current is zero. Of course, internal resistance never can be zero. However, the potential difference at the cell terminals can be measured without drawing current from the cell; under these circumstances the potential difference at the terminals is equal to the emf of the cell. This is sometimes called the **no-load** or **open-circuit** potential difference of the cell.

The concept of emf can be used to describe the action of electric cells or other energy sources. It is **NOT** proper to use the term in referring to the potential difference across a load or across a part of a load.

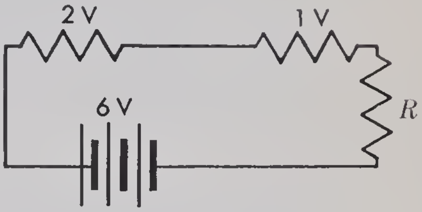
Self Check

1. A 10-Ω resistor and an 8-Ω resistor are connected in series. What is the resistance of the two combined?
2. The two resistors of Problem 1 are now connected in parallel. What is their combined resistance?
3. A 3.0-A current passes through a 6.0-Ω resistor. What is the potential difference across the resistor terminals?
4. A resistor has two terminals. Electrons enter at *A* and leave at *B*. Which is negative with respect to the other?
5. A battery has two terminals. Electrons enter at *A* and leave at *B*. Which is negative with respect to the other?
6. Which of the following expressions mean the same thing: *IR* drop, emf, potential difference across a resistor, potential difference across battery terminals?

What is the magnitude and direction of the current in the fourth wire in the following diagram?



Question 7



Question 8

8. What is the potential difference across *R* in the diagram above?
9. Why do house lights dim when the motor for the oil furnace starts?
10. The emf of a battery is 12.0 V. The internal resistance is 0.1 Ω. What is the potential difference across the terminals when the current is 2 A?

Problems

Make a diagram to show each circuit.

A 1. What is the effective resistance of a series network made up of two 75-Ω resistors, one 25-Ω resistor, and one 3-Ω resistor? Does the order in which these are connected make any difference?

2. If a certain type of wire has a resistance of 4.0 Ω/ft., what resistance does a 40-ft length have? How is this an application of resistors in series network?

3. Resistors of ⅓ Ω, ¼ Ω, and ⅕ Ω, respectively, are connected into a parallel network. What is the network resistance?

4. Resistors of 3 Ω, 4 Ω, and 5 Ω, respectively, are connected into a parallel network. What is the network resistance?

5. Resistors of 4.0 Ω, 7.0 Ω, and 12.0 Ω, respectively are connected into a parallel network, which itself is connected in series with a 4.0-Ω resistor and a 6.0-Ω resistor. What is the total resistance?

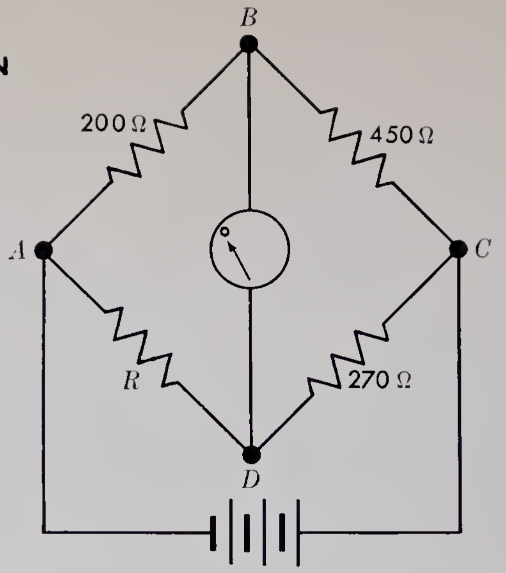
6. In Fig. 11–3a, the battery provides a potential difference of 8 V, and the current from the battery is 0.5 A. If the current through the lamp at *Y* is 0.2 A, what is the current through the lamp at *Z*? What is the potential difference across *Y*? across *Z*?

7. In Fig. 11–3a the two lamps themselves form a closed loop without a battery. Apply Kirchhoff's second rule to this loop.

8. In Fig. 11–3b, when the switch is closed the potential difference between *A* and *B* is 6 V. What is the potential difference between *B* and *C* if the battery has a potential difference of 8 V?

B **9.** Your house is 400 ft from the electric power line, which delivers electric energy at a potential difference of 120 V. Therefore, you have a special pair of feeder wires whose total resistance is 0.20 Ω. Due to an equipment failure just outside your house, the feeder lines arc and draw 180 A. What is the potential difference at your house when you turn on switches and draw an additional 20 A?

10. A rule of thumb which electronics technicians use when working with parallel networks of two resistors is that the network resistance equals the product of the two components divided by their sum. Prove that this rule of thumb is mathematically correct.



11. In the circuit shown, a sensitive ammeter shows zero current between points *B* and *D*. What is the resistance of *R*?

Discussion Questions

1. A repairman is working on a lamp. With the power on, he measures the potential difference across the terminals of the fuse, the terminals of the switch, and those of the lamp itself. The voltmeter registers 0 in two places, but shows full line potential difference when connected across the switch terminals, even though the switch is turned on. He immediately seeks a replacement switch. Why?
2. Explain how a point in a circuit can be positive with respect to another point, and yet negative with respect to a third point.

Computing Electric Power and Energy

11–21 Electric power is computed in familiar units. When a charge moves in an electric circuit, it does work. Usually this results in heating the circuit or in turning a motor. Often it is desirable to know the rate at which the work is done; that is, the electric power.

As you have learned, potential difference $= \frac{\text{work}}{\text{charge}}$. Therefore, work = potential difference × charge. Power is the time rate of doing work:

$$\text{power} = \frac{\text{work}}{\text{time}}$$

$$\text{power} = \frac{\text{potential difference} \times \text{charge}}{\text{time}}$$

$$= \text{potential difference} \times \frac{\text{charge}}{\text{time}}$$

But, since current is the flow of charge per unit time, current can be substituted for the last term. Therefore,

$$\text{power} = \text{potential difference} \times \text{current}$$
$$P = VI$$

If potential difference is measured in volts; and current, in amperes; then the unit of power is the volt · ampere, which can be shown to be the same as the watt:

$$1 \text{ volt} \times 1 \text{ ampere} = \frac{1 \text{ joule}}{\text{coulomb}} \times \frac{1 \text{ coulomb}}{\text{second}}$$
$$= 1 \text{ watt}$$

In situations where the units of the power formula are unknown or are not those desired, the formula can be combined with Ohm's law to solve problems. With Ohm's law the formula for power can be expressed in three useful forms:

$$P = VI = I^2R = V^2/R$$

11–22 Electric energy is easily computed. Electric power is the rate at which energy is delivered or consumed in all or part of a circuit. But electric services are bought and sold not in terms of power, but in terms of energy or work. The concepts of work and power are related closely. In electricity, as in all forms of energy, power is the time rate of doing work.

$$P = \text{work}/t, \quad \text{or} \quad \text{work} = Pt$$

Applying this to electricity, work in joules is equal to the product of power in watts and time in seconds. Electric energy is thus expressed in watt · seconds (joules) or in watt · minutes, watt · hours, etc. In today's energy market, a joule is a small unit indeed. Hence electric energy usually is measured in watt · hour and kilowatt · hours. The kilowatt · hour (kWh) equals a thousand watt · hours. Study Example 3.

11–23 The heat produced by electric energy is determined simply. Many electrical appliances are devices for converting electric energy into heat. By using the mechanical equivalent of heat, you can determine the amount of heat produced. One joule of work is equivalent to 0.24 calorie of heat. Study Examples 4 and 5.

EXAMPLE 3

An electric bathroom heater uses 12 amperes at 110 volts. If the cost of electricity is 2.5 cents per kWh, how much does it cost to operate the heater for 15 min?

Given: $V = 110$ volts $\quad t = 15$ min $= 0.25$ h
$I = 12$ amperes
cost-rate $= 2.5$ cents/kWh

To find: cost

Solution: energy consumed $=$ work $= Pt = VIt$
$= 110$ volts $\times$ 12 amperes $\times$ 0.25 h
$= 330$ Wh $= 0.33$ kWh
cost $=$ cost-rate $\times$ time
$= 2.5$ cents/kWh $\times$ 0.33 kWh
$= 0.83$ cents, Answer

EXAMPLE 4

How much heat is produced by a 1200-W electric iron in 30.0 min?

Given: $P = 1.200 \times 10^3$ W
$t = 30.0$ min $= 1.80 \times 10^3$ sec

To find: heat produced

Solution: work $= Pt$
$= 1.200 \times 10^3 \text{ W} \times 1.80 \times 10^3$ sec
$= 2.16 \times 10^6$ J

$$\text{heat} = 0.24 \frac{\text{cal}}{\text{J}} \times 2.16 \times 10^6 \text{ J}$$

$= 5.2 \times 10^5$ cal, Answer

EXAMPLE 5

How long will an electric heater take to raise the temperature of 500 g of water from 20°C to 80°C? The heater has a resistance of 40Ω and is operated at 120 V.

Given:
$m = 500$ g
$\Delta t = 80°C - 20°C = 60$ C°
$R = 40\Omega$
$V = 120$ V
c of water $= 1$ cal/gC°

To find: time to heat the water

Solution: calories to heat the water

$$= mc\Delta t$$

$$= 500 \text{ g} \times \frac{1 \text{ cal}}{\text{gC°}} \times 60 \text{ C°}$$

$$= 3.0 \times 10^4 \text{ cal}$$

$$P = V^2/R = \frac{(120 \text{ V})^2}{40\Omega} = 3.6 \times 10^2 \text{ W}$$

$$\text{work} = Pt = 3.6 \times 10^2 \text{ W} \times t$$
$$= 3.6 \times 10^2 \text{ J/sec} \times t$$

calories produced by heater

$$= 0.24 \frac{\text{cal}}{\text{J}} \times \frac{3.6 \times 10^2 \text{J}}{\text{sec}} \times t$$

This must equal the calories to heat the water.

Therefore:

$$0.24 \text{ cal} \times \frac{3.6 \times 10^2}{\text{sec}} \times t = 3.0 \times 10^4 \text{ cal}$$

$$t = \frac{3.0 \times 10^4 \text{ cal} \times \text{sec}}{0.24 \text{ cal} \times 3.6 \times 10^2}$$

$$= 3.5 \times 10^2 \text{ sec}$$
$$= 5.8 \text{ min, Answer}$$

Self Check

1. The potential difference across a resistor is 50 volts. What power is consumed in the resistor if the current is 4 amperes?
2. What becomes of the electric energy of Question 1?
3. What is the current through a 1200-watt heater operated at 120 volts?
4. What is the resistance of a 40-watt bulb operated at 120 volts?
5. If a 100-watt bulb operates for 1 hr, how many joules of energy does it use?
6. Is the kilowatt · hour a unit of power or of work?
7. If a heater connected to a 120-volt source draws 10 amperes, how many calories will it produce in 10 sec?
8. If the heater of Question 7 operates for 6 hr, how many kilowatt · hours does it consume?

Problems

Ⓐ **1.** An electric toaster uses 6.0 A from a 120-V line. What power does it consume?

2. A 150-W lamp consumes 150 W of power and converts it to heat and light. What current does it use when operated at its normal 120-V rating?

3. An iron using 8 A has a connecting wire whose total resistance is 0.020 Ω. What power is wasted in the connecting wire?

4. A 500-Ω resistor in a circuit has a potential difference of 5 V across its terminals. What power appears as heat in the resistor?

5. An electric bathroom heater has a resistance of 16 Ω when operating at its rated potential difference of 120 V. If the price of electric energy is 3.0 cents per kWh, how much does it cost to operate this unit for 30 min?

6. An electric iron has a resistance of 20 Ω and draws 8.0 A of current. How much heat is produced in 10 min?

7. What current is involved in the normal operation of a 120-V lamp rated at (a) 50 W; (b) 150 W; (c) 1.00 kW?

8. Use the power equation to find the resistance of each lamp in Problem 7. Check by using Ohm's law. Does a powerful lamp have a higher or lower resistance than a less powerful lamp?

Capacitors

11–24 A capacitor stores electric energy. A continuous current cannot be maintained in an open, or incomplete, circuit, but a current can exist briefly in such a circuit. Consider the circuit of Fig. 11–17 just before the dry cell is connected. When it is connected, electrons flow briefly to *A*, making it negative, and out of *B*, leaving it positive. Of course, the current lasts but a small fraction of a second until *A* has the same potential as the negative terminal of the battery and *B* has the same potential as its positive terminal. *A* very promptly becomes 1.5 volts more negative than *B*.

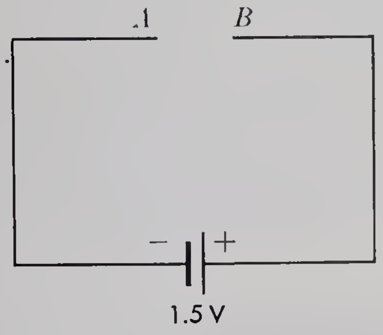


Figure 11–17 Once the cell is connected in this circuit, *A* becomes negative with respect to *B*. As a result, energy is stored in the electric field between *A* and *B*.

Electrons have moved, though briefly, and energy has been delivered by the battery. The principle of conservation of energy indicates that this energy has not been destroyed. Where is it? Can it be reclaimed?

An electric charge has been stored on *A* and *B*, and an electric field has been established between *A* and *B*. The energy has been stored in this field — literally in the space between *A* and *B*. The conductors *A* and *B* and the insulating material or empty space between them constitute a **capacitor**. (The older term, condenser, is falling into disuse.)

It is quite evident that more charge can be stored on *A* and *B* if the potential difference of the battery in the circuit is increased. Other factors also determine the quantity of charge which a capacitor will store. Other things being equal, a capacitor will store more charge if the area of the conductors *A* and *B* is increased, if the separation between the conductors *A* and *B* is reduced, or if the space (vacuum or air) between the conductors is replaced with a good insulator (Fig. 11–18).

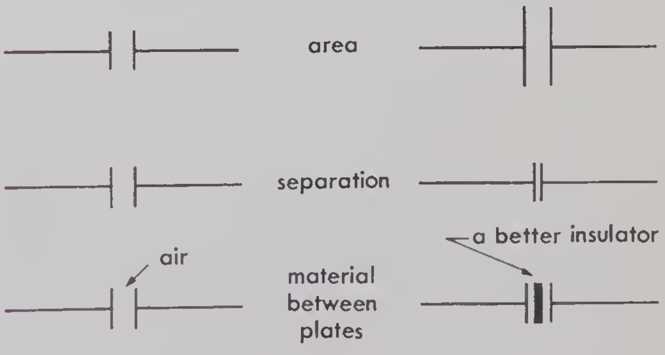
These three factors determine a capacitor's ability to accept an electric charge at a given potential difference. This ability is called the **capacitance** (C) of the capacitor. The charge on a capacitor at a given potential difference is:

$$Q = CV$$

since the charge in the capacitor is proportional to the capacitance and also to the potential difference.

11–25 The farad is the unit of capacitance. The mathematical relation above can be arranged to provide the defining equation for a unit of capacitance:

Figure 11–18 In each of the three pairs of capacitors below, the capacitance of the one on the right has been increased over that of its counterpart on the left. The cause of the increase in capacitance is indicated between each pair.



$$C = Q/V$$

Hence, the unit of capacitance is defined as that which will store 1 C of charge at a potential difference of 1 V. The unit of capacitance is called the **farad (F)** in honor of Michael Faraday, who did important pioneer work in electricity. 1 F = 1 C/V.

Actually, a farad is a much larger unit than is commonly found in practice. If a capacitor with 1 F of capacitance were made with two parallel plates 1 mm apart in air, each plate would have to be a square, 10,600 m on a side with an area of over 40 mi^2. In view of this, it is customary to use the microfarad (one millionth of a farad) as an everyday unit. This unit, 10^{-6} F, is represented by the symbol μF. Another common unit is the picofarad (pF = 10^{-12} F).

11–26 Capacitors have many practical uses. Capacitors are used very commonly in alternating-current circuits, particularly in radio circuits. They also have interesting and important uses in the direct-current circuits you are studying.

When a switch opens, electrons often continue to flow just as they did immediately before the circuit was broken. This brief persistent flow actually jumps across the gap between conductors of the switch if they are not too far apart. The resulting arc heats and corrodes the switch parts. Switches such as the circuit breaker (points) in an automobile ignition system may close and open a few hundred times per second, and therefore the contact points of the switch would need frequent replacement if a solution to this problem had not been worked out (Fig. 11–19).

As the switch opens, the electrons, which ordinarily would arc across the contact points, charge the capacitor instead. By the time the potential difference of the capacitor is great enough to cause a small spark, the points are so far apart that the spark cannot jump the gap. The capacitor is discharged harmlessly through another path in the circuit.

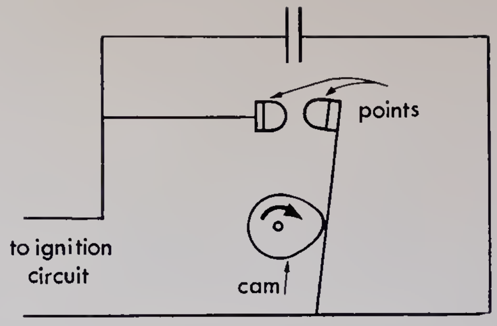


Figure 11–19 This diagram suggests the operation of the circuit breaker (points) in an automobile ignition circuit. The rapidly moving cam (with arrow) has just opened the contact points. Electrons tend to continue to surge across the gap, but instead, they charge the capacitor. This prevents arcing and greatly prolongs the life of the contact points.

Electronic flash guns employ a capacitor to store energy from a battery of cells or some other source of energy. When the photographer closes a switch, this energy is converted to light (and heat) in a specially designed gas-discharge tube.

Self Check

1. What is a capacitor?
2. What is the function of a capacitor?
3. What four factors influence the size of the charge stored by a capacitor?
4. What is a farad? a picofarad?
5. What is the capacitance of a capacitor that will store a charge of 20 μC at a potential difference of 100 V?
6. Why is the farad seldom used as a unit of capacitance?
7. Describe several uses for capacitors.

Problems

A capacitor is charged to a potential difference of 25 V. On discharge, it is found that it contained 12 μC of charge. What is its capacitance?

Chapter Summary

Electric fields exist in conductors as well as in space. These fields produce force on charged objects (particles) in the conductors, thus producing electric current. Moving charges in conductors collide with stationary particles and give up energy in the form of increased particle motion with a corresponding increase in temperature. Electric loads are usually specified in terms of the potential difference at which they should operate. This volt rating should be approximately equal to that of the source of electric energy. When current paths are arranged in series, they contain identical currents. When current paths are connected in parallel, they operate at identical potential differences. When sources of electric energy are connected in series, the total potential difference of the battery equals the sum of the individual potential differences. When sources of energy are connected in parallel, the battery potential difference equals that of any one cell, but the life of the battery is correspondingly greater.

Objects which conduct current poorly are said to have high resistance. The resistance of an object depends on the material of which it is made and its temperature, and varies directly as the length of the object and inversely as the cross-sectional area. The standard unit of electric resistance is the ohm, defined as the resistance which limits current to 1 ampere at a potential difference of 1 volt. Ohm's law sets forth the mathematical relations between current, potential difference, and resistance. Resistors connected in series have a total resistance equal to the sum of the individual resistances. For resistors connected in parallel, the reciprocal of the effective resistance is equal to the sum of the reciprocals of the individual resistances. The potential drop across a part of a load can be calculated if the current and resistance in that part are known. Kirchhoff's first rule states that the algebraic sum of all currents approaching and leaving any point in a circuit is zero. Kirchhoff's second rule states that the algebraic sum of all the potential differences around any loop of a circuit is zero. The resistance of circuit wiring and the internal resistance of sources of electric energy often make a big difference in circuit operation. Electromotive force (emf) is the actual potential difference produced by chemical or mechanical-magnetic action in cells, generators, or other energy sources. The potential difference maintained at the terminals of an energy source equals the emf reduced by the *IR* drop due to the internal resistance of the source.

Electric power is the product of potential difference times current. Electric energy, or work, is the product of power times the time interval during which power is delivered. The heat produced in a resistor can be computed from the energy delivered to it. An electric capacitor stores electric charge and consists of two conductors insulated from each other. The charge which a capacitor can store is proportional to its capacitance and to the potential difference across its terminals. The basic unit of capacitance is the farad, that capacitance which can store 1 coulomb of charge at a potential difference of 1 volt.

Vocabulary

direct current (*p. 252*)
volt rating of electric energy sources (*p. 253*)
parallel and series connections (*p. 254*)
resistor, resistance (*p. 257*)
conductor (*p. 257*)
Ohm's law, ohm (*p. 258*)
conductance, mho (*p. 259*)
IR drop (*p. 261, 262*)
Kirchhoff's rules (*p. 263*)
internal resistance of energy source (*p. 265*)
emf (*p. 266*)
electric power (*p. 268*)
watt, watt · second kilowatt · hour (*p. 269*)
capacitor, capacitance (*p. 271*)
farad, picofarad (*p. 271, 272*)

Problems

Ⓐ 1. An inexpensive home radio uses five tubes whose heaters all use 0.30 A of current. Three of the heaters have a 12-V rating, one is rated at 35 V, and one at 50 V. Can these be operated successfully from a 120-V line? What kind of connection should be used?

2. A series-connected set of Christmas-tree lamps has eight 15-V lamps. One socket becomes defective, so the owner simply removes it, and connects the other 7 lamps in series. What will be the result when he puts the seven remaining lamps into operation?

3. A given piece of wire 2.0 mm in diameter has a resistance of 0.015 Ω/m. What diameter would give it a resistance of 6.0 Ω/m?

4. A large sphere is supported on six insulating rods, each with a resistance of 10^9 Ω. If the potential difference between the sphere and the platform below is a million volts, what is the leakage current through the supporting framework?

5. You connect a sensitive ammeter in series with a 3-V battery, and complete the circuit from one hand through your body to the other hand. The meter shows a current of 0.040 milliamperes. What is the resistance of your body from hand to hand?

6. Resistors of 10, 25, and 50 Ω, respectively, are connected in parallel. In series with this combination is a resistor of 15 Ω. What is the resistance of the entire compound network?

7. A heavy-duty 4.0-Ω resistor is used as a heating element for a large room heater. A wattmeter shows that its power consumption is exactly 1 kW. What current does it require?

8. An electric clothes dryer operates at 1500 W. If it is used an average of 10 hr per week, what will the cost be to operate it for 4 weeks at 3 cents/kWh?

9. Clothes are at a temperature of 20°C when they enter the dryer of Problem 8. How many kilograms of water are evaporated each week from the clothes?

10. An electric motor operating from a 120-V line uses 7.5 A when delivering its rated power output of 0.50 hp. What is its efficiency?

B **11.** Prove mathematically that the resistance of a parallel network must be less than that of any of its components.

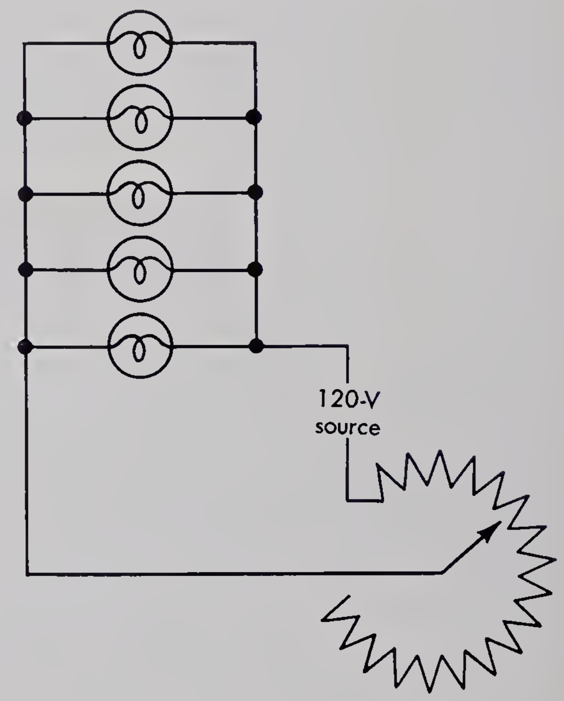
12. In a town electric energy is sold to retail customers at 4 cents/kWh. A modern kerosene lamp with a high-light-output mantle uses 2 in^3 of fuel an hour and gives as much light as a 100-W electric lamp. If kerosene costs 30 cents/gal, which source of energy is the more economical, and how does it compare with the more expensive source?

The following problems are based on the chapter introduction (p. 251).

13. The border lights at the front of the stage should have been twenty 100-W bulbs in parallel across a 120-V line. Find the total power, the total current, the resistance of one bulb, and the resistance of the parallel network.

14. A dimmer is a resistor placed in series with the circuit. The resistance of the dimmer can be varied by turning the contact point as shown in the diagram. If the lights go out when the current is reduced to 6.0 A, how much of the dimmer resistance should be put into the circuit? Assume that the resistance of the lights does not change.

In Problems 14, 15, and 16 this dimmer is used with 20 bulbs in parallel. In Problems 17, 18, and 19 it is used with a single spotlight.



15. What current exists in the dimmer when only 2.0 Ω of its resistance are in the circuit?

16. When twenty 150-W bulbs were used, what was the resistance of the parallel network? With the 150-W bulbs, and 2.0 Ω of dimmer resistance, find the current in the dimmer.

17. A similar dimmer was used on a 200-W spotlight designed to operate at 120 V. What was the resistance of the spot?

18. Find the current through the spot in Problem 17 when the dimmer was not used, and when the total dimmer resistance was used. For the lights to be dimmed effectively, the current must be reduced to considerably less than half its original value. Will the dimmer do the job?

19. What should have been the maximum resistance of a dimmer designed to work with the spot in Problem 17 if the light goes out when the current is 0.60 A?

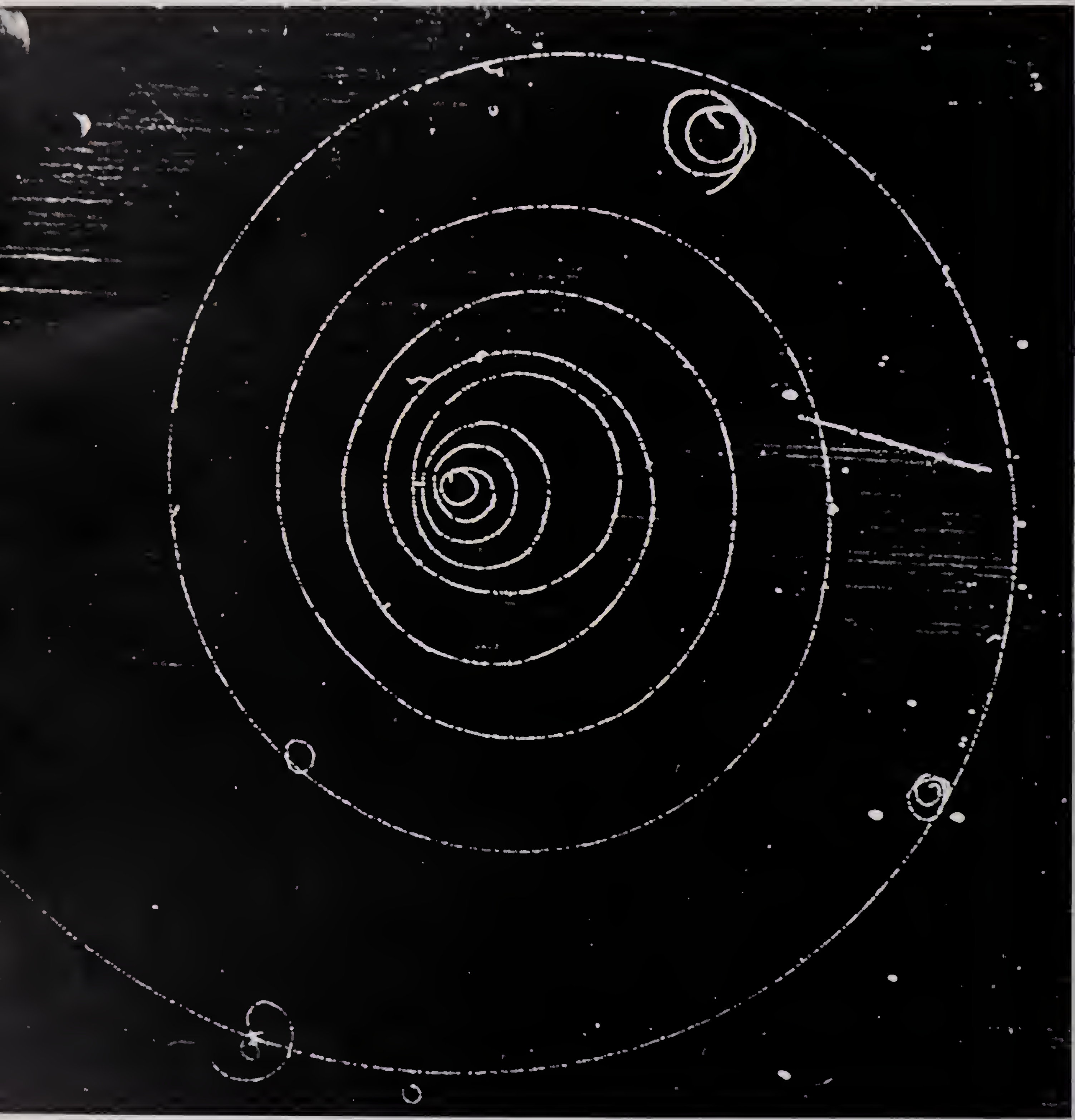
Discussion Questions

1. It is often said that no material conducts perfectly. From what you know of electron flow in solids, explain this.
2. Why are household electric appliances almost never connected in series?
3. Why does "the algebraic sum of potential differences in a closed loop is zero" state Kirchhoff's second rule better than "in a closed loop, the emf is equal to the sum of the *IR* drops throughout the rest of the loop"?
4. The starter motor of an automobile sometimes draws as much as 100 amperes. Why are the conductors from the car battery to the starting motor extremely large, being often about ¼ in. in diameter?
5. When the refrigerator goes on, the lights in the room dim and then brighten. When an electric heater is plugged in, the lights in the room may dim and stay dim. Explain what happens in each case.
6. A certain small cell has a terminal potential difference of 1.5 V under no-load conditions, but 1.1 V under normal load. What can you conclude about the condition of the cell?
7. Which of three lamps in parallel carries more current, the one with the highest or the lowest resistance? Which becomes hottest?
8. Which of three lamps in series has the largest potential difference, the one with the highest resistance or the lowest? Which becomes hottest?
9. Draw a circuit with a battery, a resistor, and a fully charged capacitor. Show that Kirchhoff's second rule applies to this circuit.
10. The heat a flatiron generates shows up mainly in the iron itself and not in the power cord as well. Why?
11. Why is it proper to say that electrons enter one plate of a capacitor while electrons leave the other plate, yet improper to say that electrons go through the capacitor?

Work on Your Own

1. Find out as much as you can about the equipment used for lighting your school stage. Determine volt ratings, power ratings, resistances of lights and dimmers, etc. Find out what equipment can be used together.
2. People often wish to estimate the cost of running an appliance before buying. Most equipment carries a label recommending volt rating and power. Estimate the number of hours a month the equipment is used. Find out the cost per kilowatt · hour charged by the local power company. Then report on the comparative costs of appliances. Which costs more to run each month, the washing machine or your desk light? an electric clock which runs all the time, or the electric toaster used a few minutes a day?
3. Find out from your electric power company the variation in the amount of potential difference supplied to houses in your community and what causes the variation. (Men working with electric power commercially often refer to the potential difference as voltage. Because this term has several meanings, it is not used in this text.)

CHAPTER 12



Courtesy of Lawrence Radiation Laboratory, University of California

A magnetic field directed upward and out of the page caused a moving electron that entered at the lower left to follow this spiral path.

Moving Charges in Magnetic Fields

In the eighteen-thirties, Thomas Davenport, a young American blacksmith, undertook a series of intensive experiments with electromagnets. He was particularly impressed with the fact that the magnetism could be turned off and on rapidly and easily. It occurred to him that it should be possible to use such a large and easily controlled form of energy for purposes more important than lifting iron. He set to work to develop the electric motor. In less than a year, he had a small crude model in operation. In two more years, he was using motors of about ⅓ horsepower — larger than those now used in washing machines and refrigerators.

At almost the same time a Russian physicist named Moritz von Jacobi was working independently toward the invention of the electric motor. Jacobi's motors looked somewhat different from Davenport's, but their principles were identical: both used two sets of interacting electromagnets with the current through one set automatically reversed by a rotary switch.

Both men developed motors whose principles underlie the direct-current motors of today. Scores of scientists and engineers who followed contributed many refinements to electrical machinery, and refinements still are being made today; but credit for developing the fundamental principles of motors and generators is properly shared by the American blacksmith and the Russian physicist.

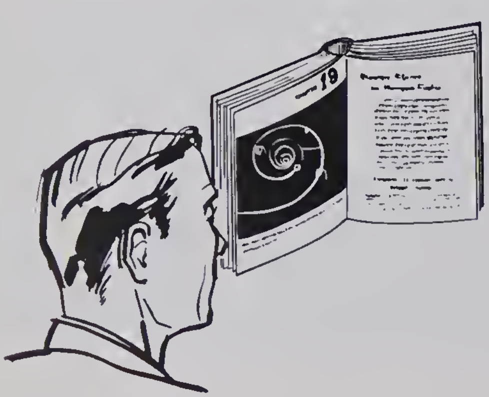
In this chapter you will learn how moving charges — whether they be free electrons in a conductor or electrons moving freely in space — are influenced by magnetic fields.

Deflection of Moving Charges by Magnetic Fields

When the pioneers in electromagnetism began to investigate the relationships between moving charges and magnetic fields, they had no understanding of the real nature of an electric current. In this respect you have a great advantage over them. You know that an electric current in a metal wire is a flow of electrons, that the electrons have a negative charge, and in what direction the electrons move. With this in your favor, you can understand the fundamental principles of electric motors and generators much better than was possible a few generations ago. Start by learning what happens when charged objects move across magnetic fields.

12–1 Magnetic fields deflect charged particles. In Chapter 4 you learned about cloud chambers and bubble chambers and their use in exploring the nature of fundamental particles of matter. The photograph on page 276 shows the tracks left by particles passing through a bubble chamber. The large spiral is the path of a single electron traveling across a magnetic field. To understand exactly what happens, hold the book as the student does in Fig. 12–1, with the page vertical and the left side of page 276 toward you. In this position the electron is moving away from you. Remember that it is crossing a magnetic field and that the direction of the field is from the viewer's left to his right in Fig. 12–1. This is as if you were shooting negatively charged corks from a popgun between the poles of a strong permanent magnet, as in Fig. 12–2. As the illustrations show, the negatively charged electrons and corks are deflected upward as they cross the magnetic field.

Figure 12–1 To analyze the behavior of the electron described on page 276, hold the book like this. Then the electron at the bottom is moving away from you, crosses a magnetic field, and is deflected upward.



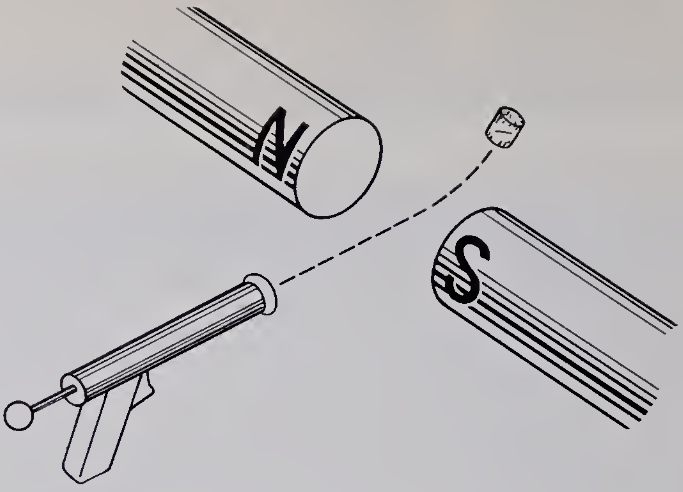


Figure 12–2 In this thought experiment a negatively charged cork, which corresponds to the electron described on page 276, moves away from you and across the magnetic field; as a result, it is deflected upward.

Try to have in mind three directions at once: 1. the movement of the charged object, which is away from you; 2. the direction of the magnetic field, in this case from left to right; 3. the deflection of the charged object, which is upward and which must be the result of an upward force. Notice that the original motion of the charged object is at right angles to the magnetic field and that the resulting force is perpendicular to both of the other directions. That is, the direction of the movement, the magnetic field, and the resulting force are all mutually perpendicular. Thus the deflection that a charged object experiences when moving across a magnetic field is perpendicular to the movement and to the field.

Do It Now

Look around the room and find two lines which are perpendicular to each other. A floor corner and a wall corner will serve. Where is a third line perpendicular to both of the others? How many such third lines are there? Would you say the three lines are mutually perpendicular?

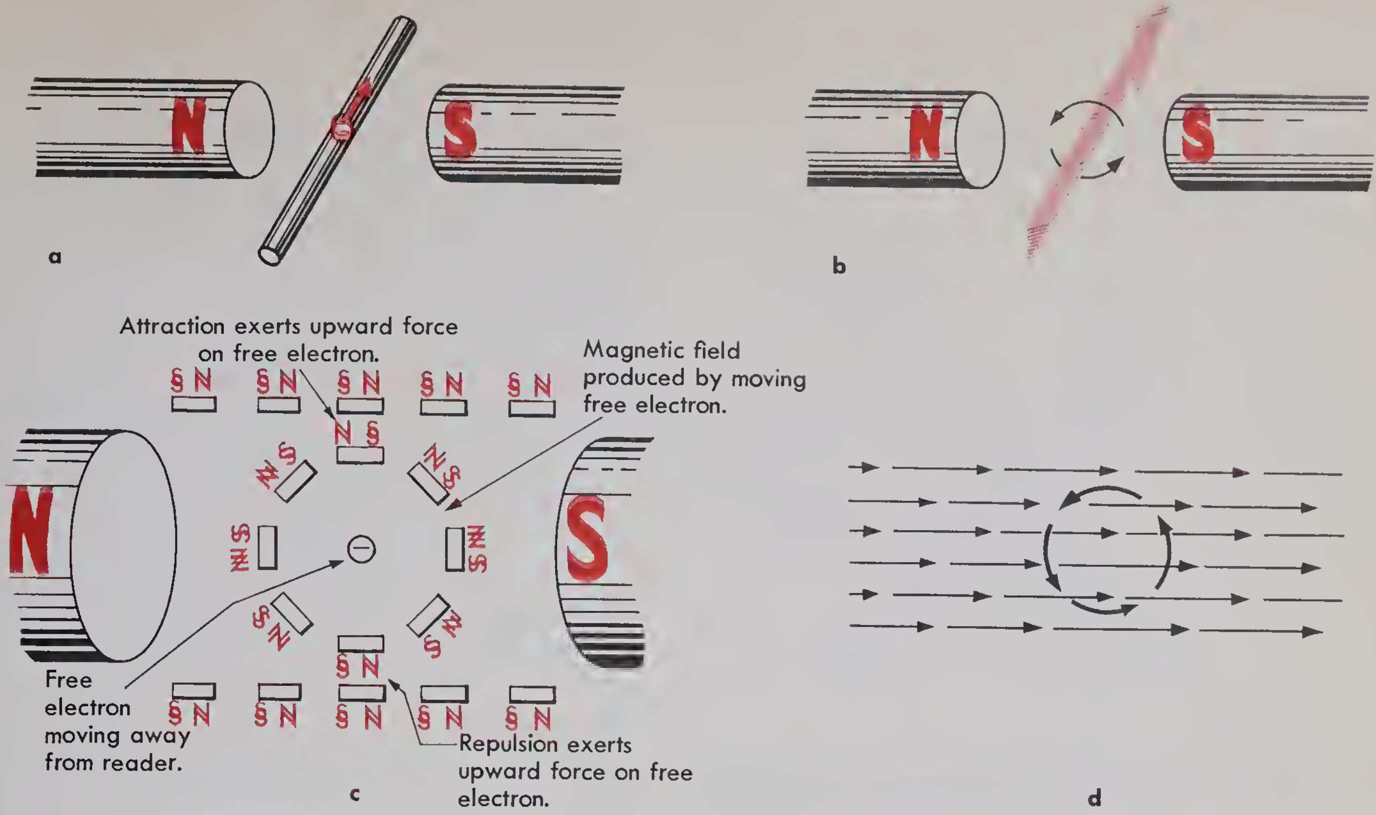

N
S
a
N
S
b
Attraction exerts upward force on free electron.
Magnetic field produced by moving free electron.
S N
N S
N
S
Free electron moving away from reader.
Repulsion exerts upward force on free electron.
c
d

Figure 12–3 This series of diagrams represents a train of thought starting with the moving electron on page 276 and the moving cork of Fig. 12–2. Remember that an electric current is a flow of electrons; hence, a moving charge constitutes a small amount of electric current. **a.** The moving charge is shown as though part of a current in a conductor. **b.** The motion of the charge is shown by the straight arrow, while the curved arrows show the magnetic field surrounding the moving charge. **c.** The field of the permanent magnet is shown by rows of imaginary bar magnets, while the field due to the moving charge is shown by the ring of magnets. **d.** Here arrows replace the magnets of **c**. In **c** and **d** the two fields are shown as though they were independent; actually, they interact.

12–2 The deflection of moving charges can be explained in terms of known principles. The analysis of the behavior of the electron in Fig. 12–1 may surprise and confuse you. However, it can be explained in terms of principles which you already know.

Study the sketches in Fig. 12–3. In the first, the electron is shown as it moves in a short section of wire. The electron which constitutes the current moves into the page, away from you, the reader. Now remember that the current in the wire produces a magnetic field around the wire; the direction of this field can be predicted from the left-hand rule. In this case, the field is counterclockwise (Fig. 12–3b).

Figure 12–3c further explains the situation. The field due to the magnet, from left to right, is shown as though made up of tiny bar magnets; think of them as a large number of tiny magnetic compasses, if you wish. The field surrounding the current is shown as a ring of tiny bar magnets. You can see that the "bar magnets" of the two fields attract each other above the conductor and repel each other below the conductor. Hence, the force on the wire is upward. Figure 12–3d represents the same situation with imaginary arrows instead of imaginary bar magnets.

12–3 A simple rule determines the direction of deflection. The kind of analysis illustrated in Fig. 12–3, if accurately done, can always be used to find the direction of the force acting on a charge moving across

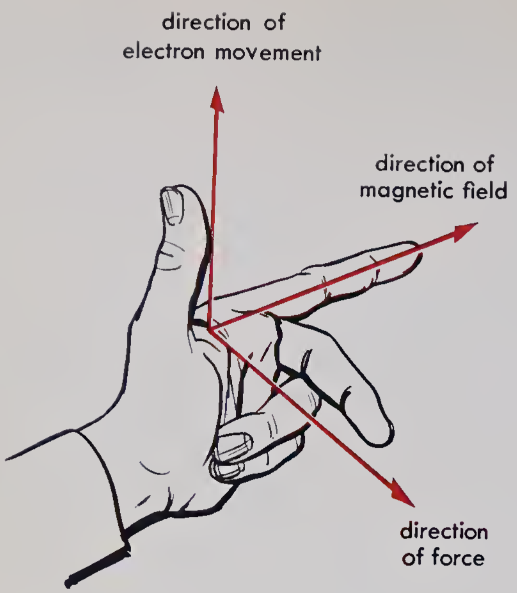


Figure 12–4 With the *three-finger rule,* using the left hand, you can predict the direction of the force on an electron moving across a magnetic field. Here the thumb represents the movement of the electron across the field; the index finger, the direction of the magnetic field; and the middle finger, the direction of the resulting deflecting force.

a magnetic field. However, some students prefer the more direct **three-finger rule** for predicting the direction. To use this rule, think of movement, field, and force in that order, and represent them by three digits of the left hand — thumb, index finger, and middle finger, respectively. Hold the three digits so that they are mutually perpendicular, as in Fig. 12–4. The thumb points in the direction of movement of the electrons, the index finger points in the direction of the magnetic field, and the middle finger points in the direction of the force experienced by the moving charge. Notice that this rule applies to moving *negative* charges. If the moving object is charged positively, the deflecting force is reversed.

You may like this rule, or you may not care for it. You may invent your own rule. Perhaps you prefer to determine the direction of the force from basic principles, as suggested in Fig. 12–3.

12–4 A charged particle may have a circular or a spiral path. Figure 12–2 shows a negatively charged cork deflected upward as it escapes from the field between the magnets. What happens to a charged particle (an electron, for example) which does not escape from the field? After it has changed direction, it still moves at right angles to the field. Therefore, it keeps on changing direction as long as it is in the field. In a uniform field, the size of the force on the electron is constant and always perpendicular to the direction of motion. Therefore, the path becomes a circle, as shown in Fig. 12–5a. In a perfect vacuum, the electron could move in a circle indefinitely. However, electrons in a cloud chamber are slowed down as they encounter other particles and therefore move in smaller and smaller circles.

Frequently when a charged particle enters a magnetic field, it is not moving exactly at right angles to the field. Figure 12–5b shows that in such cases the resulting particle path spirals around lines of force.

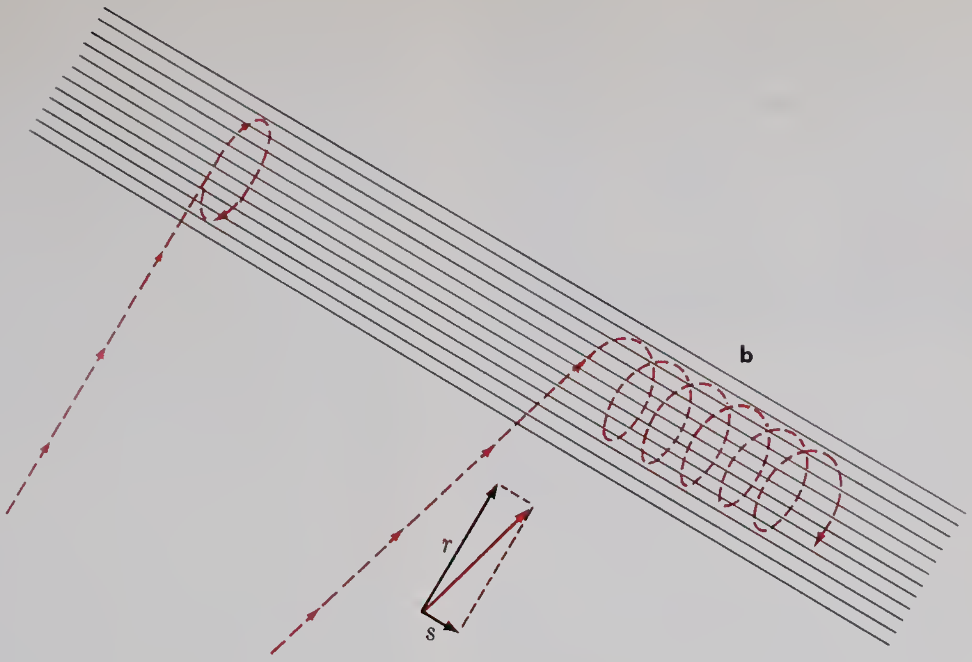
12–5 Deflection provides a definition for magnetic flux density. What determines the magnitude of the force on a moving charge in a magnetic field? The force exists because the moving charge creates its own magnetic field which reacts with the existing one. The magnetic field due to the charge depends on the size of the charge and how fast it is moving. Therefore the magnitude of the force on the charge depends on the size of the charge, its velocity at right angles to the field, and the field through which it moves. Mathematically:

$$F = BQv$$

where F is the force, Q is the charge, v is its velocity at right angles to the field, and B is a quantitative measure of the field called **magnetic flux density**.

This equation also provides a means for defining the unit of magnetic flux density.

Figure 12–5



An electron encounters a uniform magnetic field at right angles. The resulting path is a repeating circle.

An electron strikes the field obliquely. The r component produces circular motion; the s component produces uniform linear motion. Combined, the components form a spiral path of uniform pitch and diameter.

To see how this is done, first solve the equation for B:

$$B = \frac{F}{Qv}$$

Now, if a charge of 1 C is moving at 1 m/sec perpendicularly to the field, and the force on the charge is 1 N, then the flux density of the field that is causing the force is:

$$B = \frac{1\ \mathrm{N}}{1\ \mathrm{C} \times 1\ \mathrm{m/sec}} = 1\ \frac{\mathrm{N \cdot sec}}{\mathrm{C \cdot m}}$$

Thus the unit of flux density might be called a newton-second per coulomb-meter. However, it has been given another name, the **tesla** (T). The flux density of a magnetic field is 1 T if a charge of 1 C experiences a deflecting force of 1 N when it moves perpendicularly across the magnetic field with a velocity of 1 m/sec.

The flux density of a field tells you something about how concentrated the field is. Sometimes you are interested also in the total flux through a certain area. In Fig. 12–3, for example, you might wish to know the total flux through the area between the two magnets. To find the total flux, Φ (the Greek letter, *phi*), you multiply the flux density by the area that is perpendicular to the field:

$$\Phi = BA$$

If flux density (B) is in teslas and the area (A) is in square meters, the flux (Φ) is in **webers** (**Wb**).

$$\Phi = \mathrm{T} \times \mathrm{m}^2 = \mathrm{Wb}$$

Here is a summary of these new units:

	symbol	*unit*	*abbreviation*	*defining equation*
magnetic flux density	B	tesla	T	$B = F/Qv$
magnetic flux	Φ	weber	Wb	$\Phi = BA$

A magnetic flux density of 1 T is quite strong. The largest flux densities produced in laboratories are less than 100 T; the magnetic field of the earth is of the order of 10^{-5} T.

The formula $F = BQv$ enables you to compute the magnitude of the force on a moving charge in a magnetic field.

Self Check

1. Account for the force on a charge moving in a magnetic field.
2. The poles of a U-magnet are arranged with the N-pole directly over the S-pole. A negatively charged object passes between the poles from your left to your right. What is the direction of the resulting force?
3. What is the direction of the force if a positively charged object is moving away from you across the magnetic field of Question 2?
4. What is the path of an electron that enters a field at an angle of 60° to the field?
5. In what terms is the standard mks unit of magnetic flux expressed?
6. Define a magnetic flux density of 1 T.

Problems

A **1.** The magnetic flux through a rectangle 10 cm × 40 cm is 0.0010 Wb. What is the average magnetic flux density in this region?

2. What magnetic flux density is required to produce a deflecting force of 0.0010 N on a charge of 0.0075 C moving perpendicularly across it with a velocity of 30 m/sec?

3. What deflecting force is exerted on a charge of 40 μC moving at 15 cm/sec perpendicularly across a magnetic field whose flux density is 0.025 T?

4. A square hole 12 cm on a side is oriented with its plane perpendicular to a magnetic field of 40×10^{-2} T. What is the total quantity of magnetic flux through this hole? What is the flux through the hole if its plane is oriented 30° from the direction of the field?

B **5.** A particle with charge Q, mass m, and velocity v, enters a field of flux density B at right angles to the field. It travels in a circle in the field. Express the radius of this field algebraically. How could you use this equation to discover something about the alpha particles in a cloud chamber?

Discussion Questions

1. What happens to the motion of an electron that is moving in the *same* direction as a magnetic field which it enters? in the *opposite* direction?
2. What is the advantage of using the logic of Fig. 12–4 to predict the direction of force acting on a charged particle moving across a magnetic field?

Magnetic Fields Can Control Charged Particles

12–6 The mass spectrometer separates and collects charged particles. One of the most useful devices in modern research physics and in industrial engineering is the **mass spectrometer**. This instrument makes it possible to separate charged particles on the basis of their mass and to measure their relative abundance. The underlying principle of its operation is the deflection of moving charges by magnetic fields.

Suppose scientists wish to study the isotopes of a special sample of lithium. The element (or a compound containing the element) first is ionized. Each lithium atom is stripped of its outermost electron, and therefore bears a positive charge. The ions are then accelerated by charged electrodes and pass through the instrument as a beam in which all particles have the same charge Q, move at approximately the same velocity v, and cross the same field of flux density B. (See Fig. 12–6.)

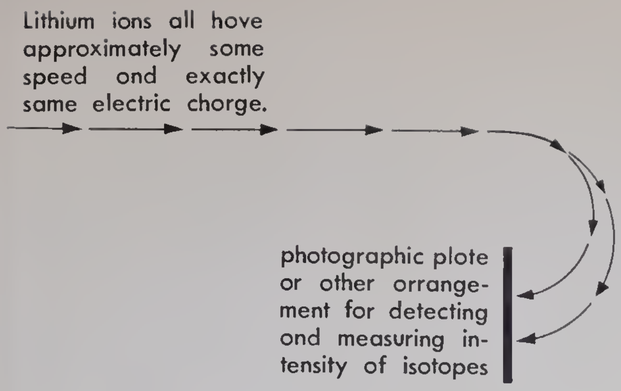

Lithium ions all have approximately same speed and exactly same electric charge.
photographic plate or other arrangement for detecting and measuring intensity of isotopes

Figure 12–6 In the mass spectrometer, isotopes of different mass are deflected into circular paths of different radii. This diagram shows two of the isotopes of lithium. One has a mass of about 6 u, the other has a mass of about 7 u. The lighter one describes the smaller arc.

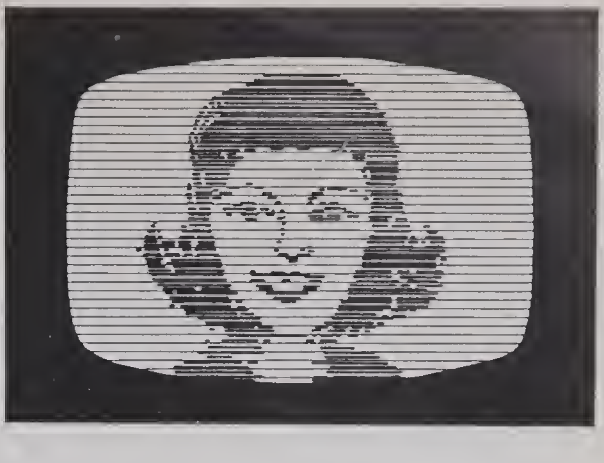


Figure 12–7 Each picture, or frame, of a TV picture is made up of a series of horizontal lines of variable intensity. Each second there are 30 complete frames, each made up of 525 lines.

It is evident, then, that the charges experience approximately the same deflecting force. The apparatus is large enough to keep the particles from escaping; they therefore move in a circular path. Since the particles are isotopes of the same element, they have slightly different masses. Therefore, lighter isotopes are deflected into a smaller circle than the heavier ones. In this way, the mass spectrometer can be used to separate and measure isotopes.

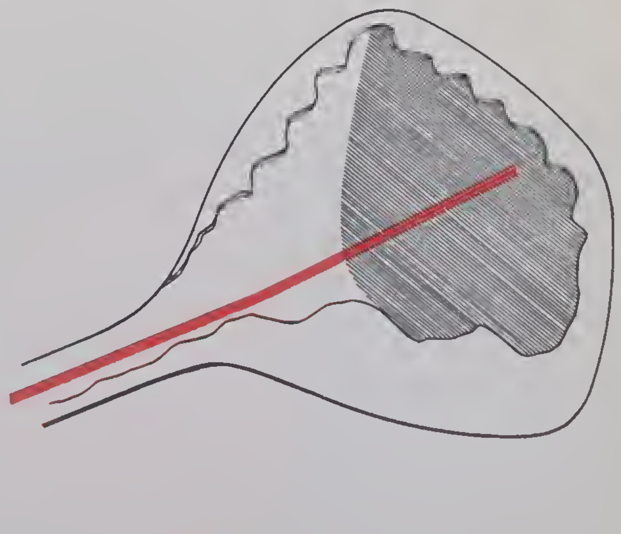
Similarly, uranium isotopes ${}_{92}U^{235}$ and ${}_{92}U^{238}$ can be separated for use in nuclear reactors. The separation problem is difficult because ${}_{92}U^{235}$ constitutes only 0.7% of natural uranium. Yet this process was used during World War II to help obtain enough ${}_{92}U^{235}$ to make the first nuclear explosions on earth.

12–7 Magnetic fields help produce television images. Since a magnetic field changes the path of a moving electron, a properly designed field can direct electrons wherever the designer wishes. In a television picture tube it is essential that electrons strike the face of the tube in a particular spot. In TV receivers the electron beam is focused by properly designed electric and magnetic fields.

An image on a television screen is actually a series of still pictures in rapid sequence. As in motion pictures, the impression of motion is only an illusion. But in TV, you do not see even one complete picture at any instant. Each picture on the screen — there are 30 complete pictures every second — is sketched by a moving spot of varying intensity, as suggested in Fig. 12–7. The spot is produced as electrons strike the material on the inside of the picture tube and produce visible light.

This action is illustrated in Fig. 12–8, a view of the inside of a TV picture tube. To produce a single complete image or frame, the spot traces 525 lines. This means that the electron beam makes 15,750 horizontal

Figure 12–8 As seen from the inside of the picture tube, the electron beam moves from right to left. For each complete frame it traces out 525 horizontal lines. At any one instant, however, the beam strikes only one spot on the face of the picture tube.



trips every second, while also making a much smaller number of vertical trips. Obviously, the electron beam must be controlled with great speed and precision. In practically all TV image tubes — the camera types in the studios and the picture types in home receivers — this deflection is produced by sending the electron beam across magnetic fields.

12–8 The earth's magnetic field traps charged particles in the upper atmosphere. Ever since the discovery of cosmic rays, scientists had been sending up instruments, first to the tops of mountains, then into the air in balloons and rockets, to measure the intensity of the primary rays which are composed of charged particles. They had always found more particles at greater distances from the earth. Accordingly they were delighted to have a chance to put their counting devices aboard the first United States satellite, Explorer I, early in 1958. As expected, the count rose as Explorer I went up. However, it increased more rapidly than had been predicted. Then, to everyone's surprise, at a height of 500 to 600 mi, no particles at all were counted.

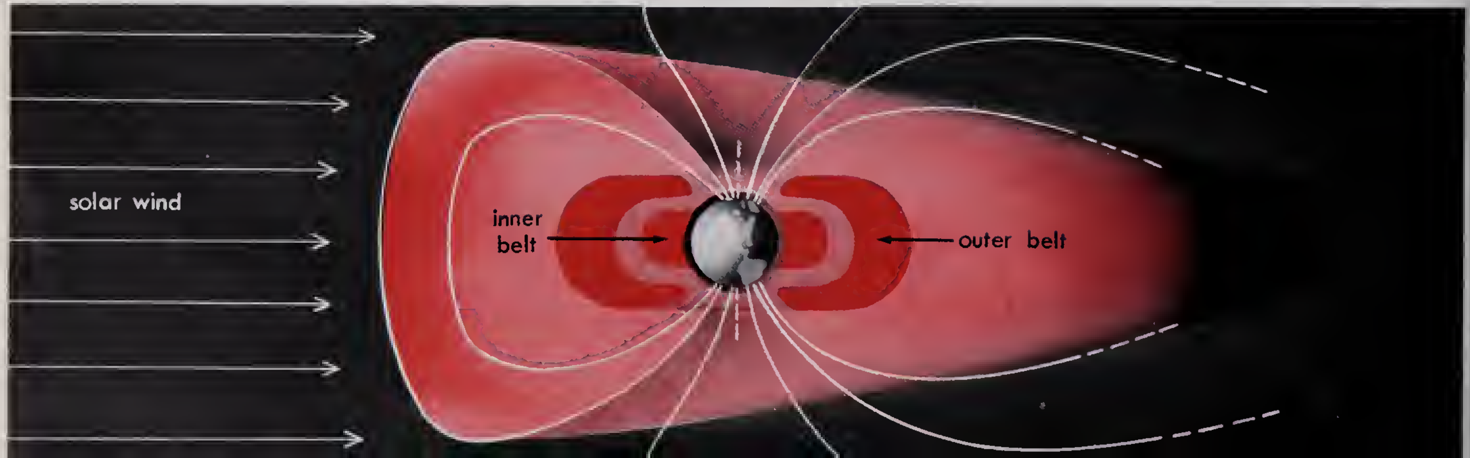
The physicists thought that the instruments had not functioned properly. A few months later, however, the instruments on Explorer III gave the same result. One scientist remembered that too many particles will cause a counter to jam and stop counting. Could it be that 500 or more miles away, there were too many particles in space for the counters to handle?

Counters that would not jam as easily were built. Up they went in Explorer IV and in Pioneer IV, a space rocket. Sure enough, a region beyond the atmosphere had a tremendous concentration of particles. There appeared to be two radiation belts. More and more satellites with newer instruments were sent up to investigate. So great is the radiation in the belts that you would not be safe there in a space vehicle unless you went through very quickly. The belts are called the **Van Allen radiation belts** after James A. Van Allen, who led the scientific team which made the discoveries. See Fig. 12–9. Beyond the belts, extending 40,000 miles into space, is a region where particles are less concentrated. The whole region, including the belts, is called the *magnetosphere.*

Why should the particles be more concentrated than predicted? Look again at Fig. 12–5b. If an electron or proton enters a magnetic field at an angle that is not 90°, it spirals along a line of force. Perhaps, then, the shape and strength of the earth's magnetic field have something to do with the Van Allen belts. Figure 12–10 depicts the

Figure 12–9 Van Allen belts and the magnetosphere. The inner belt consists mainly of high-speed protons; the outer one, of high-speed electrons. Slower protons and electrons fill the shaded area. The curved lines in the drawing show the shape of the earth's magnetic field, which is blown out of shape by the "solar wind," a stream of particles coming from the sun. Notice that the safest route for an astronaut leaving the earth is above the poles, through the hole in the doughnut-shaped belts.

(Redrawn from *Scientific American*, May, 1963, p. 86, with permission of the publishers and of the author, Mr. B. J. O'Brien.)



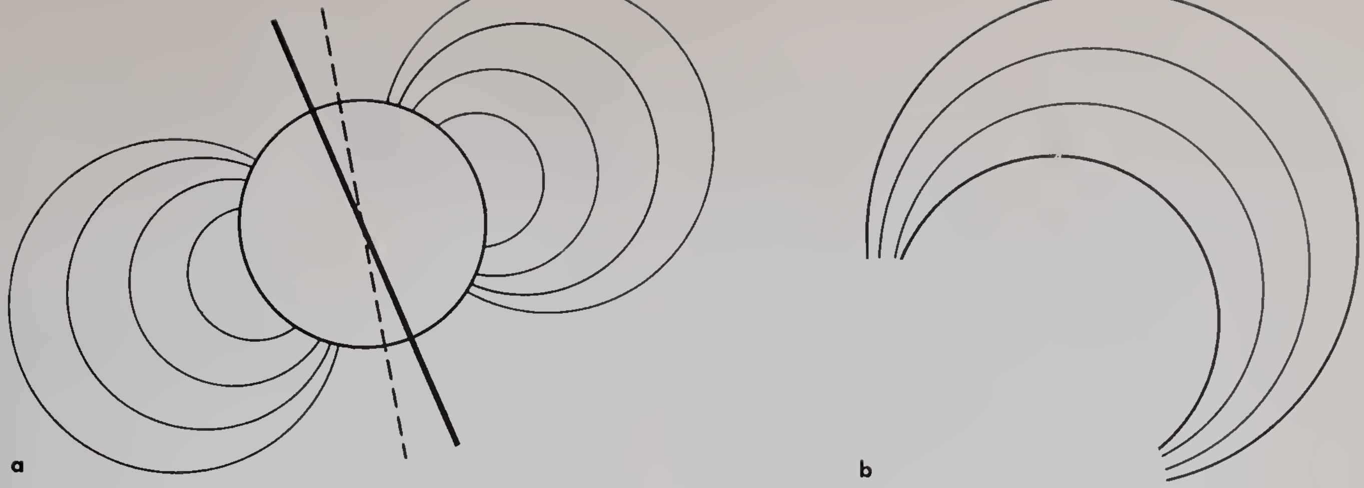


Figure 12–10 a. This diagram suggests the nature of the earth's magnetic field. The dotted line is the earth's geographical axis; the solid line is its magnetic axis. b. This diagram suggests that a section of the earth's magnetic field is shaped like a highly curved and very symmetrical banana.

earth's magnetic field in cross section, as if its lines of force were real and visible. Notice that the field is curved and that its flux density increases as it approaches the earth near the polar regions. If in imagination you take a section out of this field, it would look like a banana (Fig. 12–10b). You could describe it as being curved and as conical near its ends.

How does a charged particle behave when it encounters a field like this? If it enters the field perpendicularly, it moves in repeating circles (Fig. 12–5a). But chances are that it enters the field obliquely, as in Fig. 12–5b. Then it would spiral around the "banana" toward one end. Remember that as the particle spirals toward the magnetic pole, the field converges and becomes stronger. The result is that the spiral becomes tighter, and also that there is more force, which tends to slow the particle's progress toward the end of the crescent. Finally, the particle reverses its poleward drift and spirals back toward the magnetic equator and on toward the opposite magnetic pole. This process is repeated again and again. Scientists think that particles may make their spiraling journey from one pole to the other within a few seconds.

Because of this action, electrons and protons are virtually trapped in the earth's magnetic field. No wonder they are in greatest abundance out beyond most of the earth's atmosphere. When the supply of particles from the sun is particularly intense, the trapped particles tend to spill out one or two thousand miles from the earth's magnetic poles. In an action similar to that of a neon lamp, these particles produce the aurora borealis (northern lights) and aurora australis (southern lights) in the rarefied atmosphere a few score miles above the earth.

Of course, the whole theory is far more complicated, and parts of it are still in the realm of hypothesis. Other charged particles may be involved and may produce effects beyond those described. There are disagreements about the origin of the particles. The whole situation illustrates the unexpected and valuable knowledge and understanding which often emerge from research.

12–9 Magnetic fields can control charged particles in nuclear reactors. Reactions involving the fusion of nuclei have been achieved in the laboratory and in thermonuclear explosions (H-bombs). Physicists currently are trying to develop a technique for obtaining useful energy from controlled nuclear fusion reactions. Although research scientists feel sure that this will be accomplished soon, serious obstacles remain to be overcome. One is that the reactions occur only at temperatures of about a million degrees Celsius. To keep the reaction progressing, however, the subatomic particles involved must be very close together. This requires the use of a container. But what container will withstand such enormous temperatures?

One possible solution may be the confining of the reacting particles within a magnetic field. Many proposals for doing this have been tried, but none has been successful to date. The prospects are exciting, since controlled thermonuclear reaction would use relatively abundant fuels. Furthermore, there appears to be a good possibility that such reactors may be free from dangerous radiation.

The charged particles in such a reactor constitute what is called a **plasma**. All of the atoms are ionized, and there are approximately equal numbers of positive and negative particles. A plasma is sometimes called a fourth state of matter, in addition to solids, liquids, and gases.

Thus, the behavior of charged particles in nuclear reactions can be controlled according to the by-now familiar principle: When a charged object moves across a magnetic field, it experiences a force perpendicular to its movement and to the field.

Self Check

1. For what purpose is a mass spectrometer used?
2. If two particles of the same charge but of different mass move with the same velocity across a magnetic field, which is deflected more?
3. In a mass spectrometer, how are the ions accelerated?
4. How is the electron beam in a TV tube made to move across the screen?
5. Why do typical charged particles which are trapped in the earth's magnetic field not fall to the earth?
6. What are the Van Allen belts?
7. How might magnetic fields help a controlled thermonuclear reaction?
8. What is a plasma?

Discussion Questions

1. Which electrons in a TV picture tube are unaffected by the magnetic focusing field?
2. It is known that electron radiation from the sun is particularly intense during periods of sunspot activity. Why are such periods often accompanied by auroral activity?

The Motor Effect

12–10 A magnetic field can move a current-bearing wire. The student in Fig. 12–11 is finding out what happens when he places a wire with current in it across the magnetic field of a powerful permanent magnet. The wire is part of a simple circuit which includes the cell. The emf of the cell and the resistance of the circuit are such that the current is a few amperes. If you were to do this experiment, here is what you would find out:

a. When the wire has current and is placed *across* the magnetic field it experiences a force.
b. When the wire has current and is placed well away from the magnet, it experiences no force.
c. When the wire has no current and is placed *across* the magnetic field, it experiences no force.

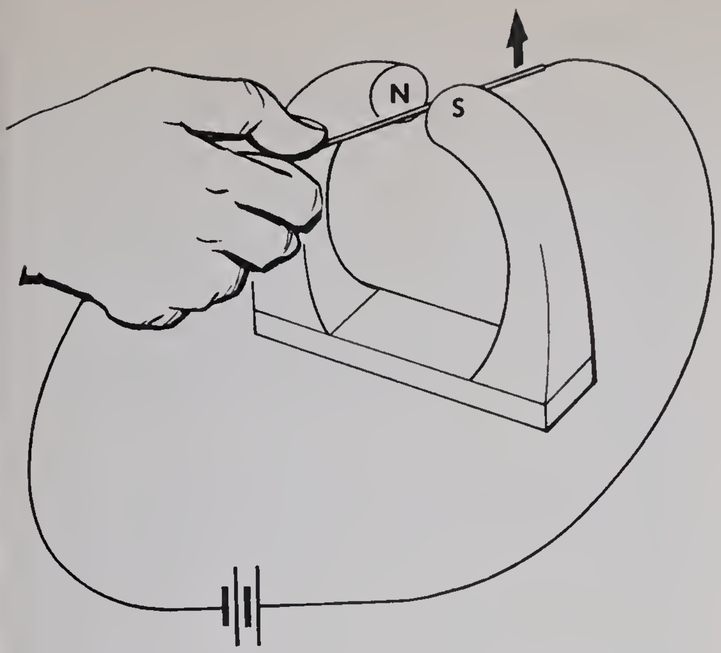


Figure 12–11 A wire is held horizontally across a magnetic field. As electrons flow toward the upper right, the wire itself is forced upward.

d. When the wire has no current and is placed well away from the magnet, it experiences no force.

e. When the wire has current and is placed parallel to the magnetic field, it experiences no force.

From these observations you can conclude (1) that there must be current in the wire and (2) that the current direction must be *across* the magnetic field for there to be a force on the wire.

f. When the wire conducts electrons away from you, the wire experiences a vertical force.

g. When the wire conducts electrons toward you, the wire experiences a vertical force opposite to that in (f) above.

From these observations you can conclude that the direction of the force on the wire is at right angles to the direction of current and also to that of the magnetic field. It also appears that the direction of current influences the direction of force.

h. If the magnet poles are reversed, the direction of the force on the wire is reversed.

From this observation you can see that the direction of the magnetic field influences the direction of the force.

i. If you vary the intensity of the current in the wire, the magnitude of the resulting force varies accordingly.

From this you can conclude that the force on the wire is directly dependent on the intensity of the current.

j. If you substitute weaker or stronger magnets, the magnitude of the resulting force varies accordingly.

From this you can conclude that the force on the wire is directly dependent on the flux density of the magnetic field.

Because the principle underlying this experiment also underlies the operation of electric motors, existence of a force on a current across a magnetic field is called the **motor effect**.

The motor effect should be neither surprising nor mysterious to you. After all, an electric current is a flow of electrons. These experience a deflecting force as they move across a magnetic field. Since they cannot escape the wire, they take the wire with them as they are deflected.

The three-finger rule (p. 280) also applies to the deflection of a current-carrying wire across a magnetic field. Use the left hand in the same way. Be sure the thumb points in the direction of electron flow—from negative to positive.

12–11 The force due to the motor effect is easily computed. In many practical situations, particularly those involving electric motors, it is useful to know the magnitude of the force due to the motor effect. On p. 280 you learned that the force on a particle moving across a magnetic field can be computed by the formula:

$$F = BQv$$

Now convert this into a formula which involves not charge Q but electric current I.

You know that current is charge per unit time:

$$I = Q/t \quad \text{or} \quad Q = It$$

Substituting in the force equation:

$$F = BItv$$

Velocity is distance, l, divided by time, t, where l is the distance traveled by a particle while in the field. If the particle is traveling in a wire, l is the part of the wire in the field. Again substituting in the equation:

$$F = BIt\frac{l}{t}$$

This in turn is equivalent to:

$$F = BIl$$

That is, the force in newtons due to the motor effect is equal to the product of the flux density in teslas, the current in amperes, and the length of the conductor in meters.

12–12 A current loop placed in a magnetic field will rotate. When the wire in the experiment of Fig. 12–11 moves, it could be made to do useful work. Obviously, this movement represents energy. What is the source of this energy? It cannot come from the magnetic field, which is as strong as it was before the experiment was performed. The mechanical energy must come from the electric energy supplied by the cells in the circuit. This basic principle underlies the operation of electric motors, although many modifications are needed to transform this experiment into a useful rotating electrical machine.

A simple electric motor has a loop of wire (**armature**) free to rotate in a magnetic field, as in Fig. 12–12. If electrons recede in side A of the loop, the resulting force makes that conductor rise. At the same time, the approaching electrons in side B of the loop force it down. As a result, the loop rotates counterclockwise until A is on top and B is at the bottom. The inertia of the loop carries it slightly past this point, but then the loop moves back to the vertical position, which is as far as it can go.

To obtain continuous rotation, the current in the loop must now be reversed. This is accomplished by using a pair of split rings (**commutator**), as in Fig. 12–12b. The split rings are mounted on the same

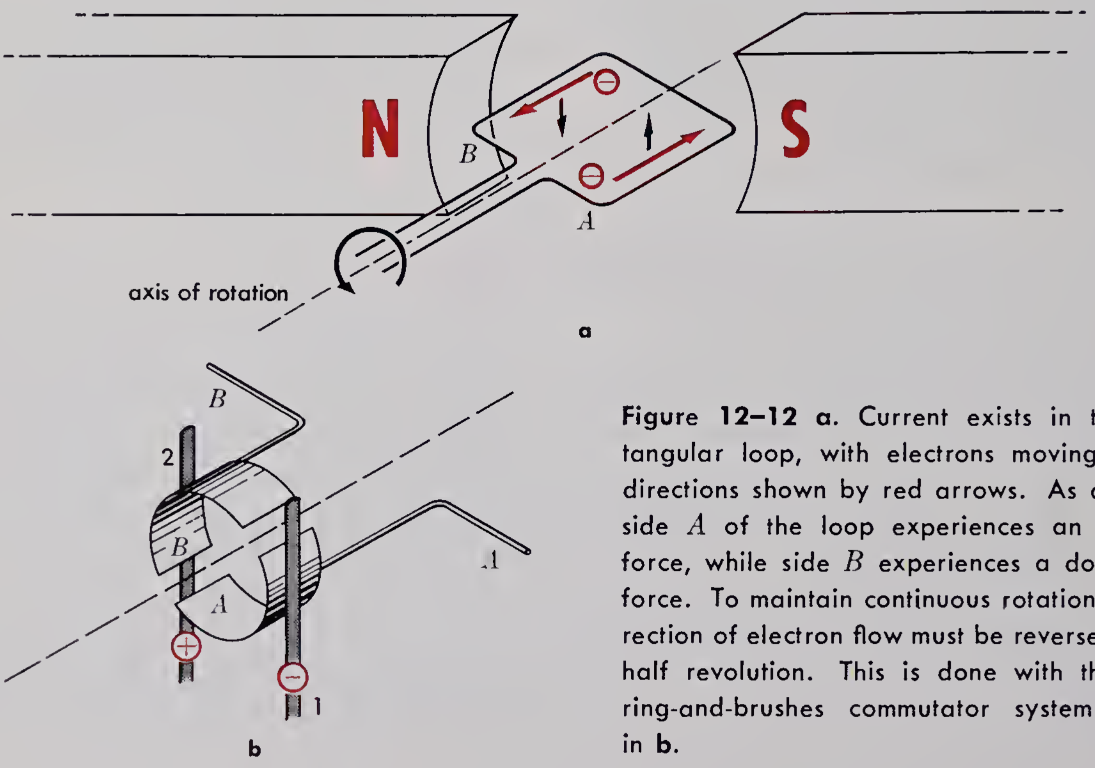


Figure 12–12 **a.** Current exists in the rectangular loop, with electrons moving in the directions shown by red arrows. As a result, side A of the loop experiences an upward force, while side B experiences a downward force. To maintain continuous rotation, the direction of electron flow must be reversed every half revolution. This is done with the split-ring-and-brushes commutator system shown in **b.**

shaft as the loop and rotate with it. The two flexible conductors (**brushes**), are fixed and rub on the split rings as they rotate. For one half of a revolution, brush No. 1 touches split ring *A* while brush No. 2 touches split ring *B*. Since brush No. 1 is negative, electrons flow into *A* and out of *B*. One-half revolution later, brush No. 1 touches split ring *B* and brush No. 2 touches split ring *A*; and electrons flow into *B* and out of *A*. Thus, the direction of current in the rotating loop is reversed automatically every half revolution.

12–13 Common electric motors have certain features. Although Fig. 12–12 illustrates the principles of a simple direct-current motor, it does not resemble a practical motor in appearance. Some of the common terms used to describe important parts of a direct-current motor are:

Field core and winding — the iron core and the turns of wire which produce the constant magnetic field. In almost all dc motors, the field is the stationary outer part, or *stator*.

Armature core and winding — the iron core and the turns of wire which experience the force due to the motor effect. In almost all dc motors, the armature is the rotating inner part, or *rotor*.

Commutator segments — the split ring mounted to the armature shaft. The name comes from *"commute,"* which means *"to go back and forth."*

Brushes — the conductors which rub against the rotating commutator segments. In early motors, these often were made of many strands of fine copper wire — almost literally a copper brush. In modern motors, brushes are usually rods of specially prepared graphite.

Stator — the stationary part of the motor.

Rotor — the rotating part of the motor.

Practical dc motors differ from the motor of Fig. 12–12 in these respects:

The fields are produced by an electromagnet, which can be connected in series with the armature winding (**series wound**) or in parallel (**shunt wound**) or in a combination of the two (**compound wound**).

The pole faces of the fields are curved, and the space within the armature winding is filled with iron. The resulting high relative permeability of the motor parts increases the flux density and raises the efficiency and power of the motor.

The armature windings have many turns — sometimes several hundred.

There are usually several commutator segments, sometimes a dozen or more. This gives the motor greater power and smoother performance. Simple motors have only two brushes, however.

In some motors, the armatures bear little resemblance to the loop in Fig. 12–12; they look more like a series of electromagnets mounted radially around the axis. Sometimes the operation of such motors is explained, not on the basis of the principle given on page 286, but in terms of attraction and repulsion between the armature poles and the field poles. Such an explanation is valid; however, the one derived from the basic principle on p. 286 is closer to fundamental theory and, therefore, more general in its application, and more useful to you as a student of physics.

Do It Now

Examine a dc motor or a universal motor, such as those found on vacuum sweepers, sewing machines, and model locomotives. Can you find the parts listed on pages 288 and 289? (The motors in washers, driers, refrigerators, and shop tools usually are different, having no brushes or commutator segments.)

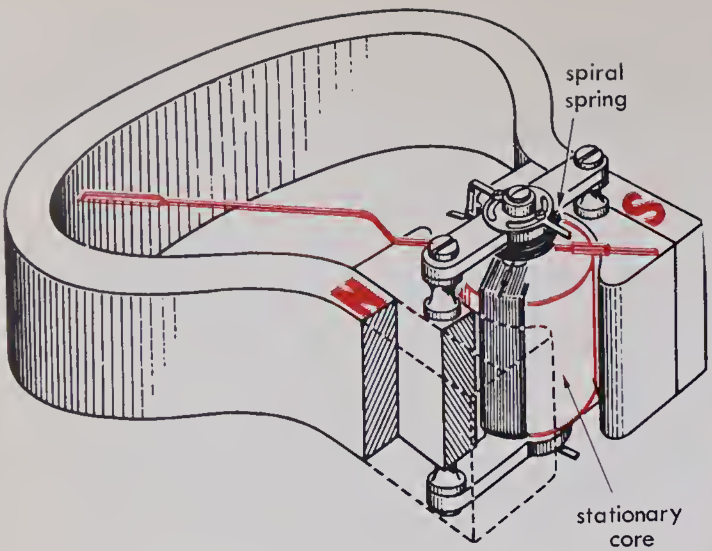


Figure 12–13 The moving coil of this meter movement has a spiral spring above and below it. Electrons are conducted in through one spring, through the coil of wire, and out through the other spring. As a result, the pivoted coil moves, swinging the attached pointer across the scale of the meter.

12–14 The operation of electric meters depends on the motor effect. The operation of many electric meters is almost identical to that of an electric motor. Figure 12–13 shows the construction of a *permanent-magnet, moving-coil, meter movement.* The core is stationary, permitting the coil (corresponding to a motor armature) to be very light in weight and, hence, easily moved. Note also that there is no commutator; electrons enter and leave the coil through the two spiral springs above and below it.

When current exists in the coil, it behaves like the armature of a motor, moving because of the force acting on its conductors. As the coil moves, the springs are wound, or unwound, and exert a back twisting force or torque on the coil. When the back torque of the spring just equals the torque developed by the coil, the meter comes to rest. The deflection is directly proportional to the torque, which in turn is directly proportional to the current producing it.

In a permanent-magnet, moving-coil type of meter movement, the needle moves because a current crosses a magnetic field, producing a sideways force on the conductor. Only current causes such a meter to deflect, whether the meter measures current, potential difference, light intensity, or engine revolutions per minute. A sensitive current-measuring meter is called a **galvanometer** Figure 12–14 shows how a galvanometer is used in ammeters and voltmeters.

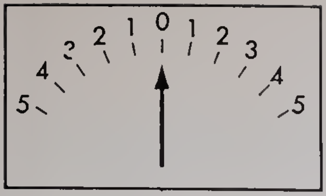
Self Check

1. Why is the three-finger rule for the motor effect the same as that for electrons moving in space?
2. What is the direction of the deflecting force on a stream of alpha particles moving away from you across a magnetic field whose direction is down?
3. A wire 20 cm long carries a current of 1 A in a field of 1×10^{-2} T. Another wire 10 cm long carries a current of 3 A in a field of 2×10^{-2} T. Which experiences the greater force? How much greater?
4. What energy change occurs in an electric motor?
5. What is the armature in a motor?
6. Why are brushes and a split ring needed in a motor such as that in Fig. 12–12?
7. What is the name of the split ring in a motor?
8. Why are brushes and split ring unnecessary in an electric meter?
9. How can a galvanometer be arranged to be used as a voltmeter?

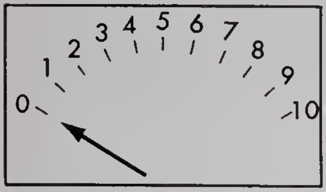
Problems

A 1. A wire 12 m long hangs perpendicularly across a magnetic field whose flux density is 0.015 T. How great must the current be to produce a motor-effect force of 1.0 N?

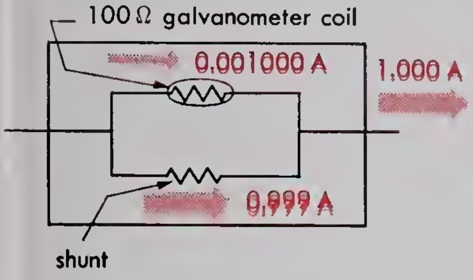
2. A single conductor of a power transmission line is 40 m long and carries a dc current of 80 A. It lies perpendicularly across the earth's magnetic field somewhere in Canada; the field is 20×10^{-6} T. What is the magnitude of the resulting force?



The needle of this galvanometer will deflect to one of the points marked 5 when there is a current of 500 μA (0.000500 A) in the coil. It is used primarily to see whether or not a current exists when only a very small current is expected. The needle is set to read 0 in the middle so that the user can tell the direction of the current. For purposes of illustration, assume that the coil of this galvanometer has a resistance of 100 Ω.



The same galvanometer can be converted into a meter movement with the zero deflection at the left end of the scale, as shown here. In that case, the galvanometer would measure up to 1000 μA (0.001000 A). When the 0 is not in the middle of the scale, the current meter must be connected correctly in the circuit, so that the coil does not twist to the left; such a twist might bend the needle or damage the coil.



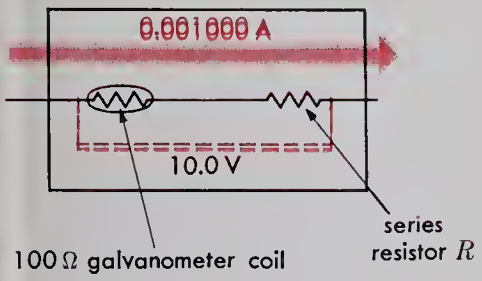
To convert the same meter movement into an ammeter for measuring a maximum current of 1.000 A, place a resistor in parallel with the coil. The added resistor is called a *shunt*. The maximum permissible current in the coil is 0.001000 A. Therefore the shunt must carry the rest of the current, or 0.999 A, as shown here. Since the shunt and the coil are in parallel, the IR drop is the same in each:

$$0.999\text{ A} \times R_{\text{shunt}} = 0.001000\text{ A} \times 100\ \Omega$$

$$R_{\text{shunt}} = \frac{0.1000}{0.999}\ \Omega$$

$$= 0.1001\ \Omega$$

For all practical purposes, in this case, a 0.1-ohm shunt will make this galvanometer into an ammeter with a full scale reading of 1 A. An ammeter is connected in series in a circuit. It has a low resistance compared with the resistance of the rest of the circuit.



To convert the same meter movement into a *voltmeter* with a maximum reading of 10.0 V, add a resistor in series with the meter movement, as shown at the left. The current through the coil must still be limited to 0.001000 A, and this is also the current through the series resistor. The total IR drop must be 10.0 V:

$$0.001000\text{ A}\,(R + 100\ \Omega) = 10.0\text{ V}$$

$$R + 100\ \Omega = \frac{10.0\text{ V}}{0.001000\text{ A}}$$

$$R = 10{,}000\ \Omega - 100\ \Omega$$

$$R = 9{,}900\ \Omega$$

The deflection of the needle of a voltmeter is caused by current, but since the resistance in the meter is fixed, the dial can be calibrated (marked) to read IR (volts) instead of amperes. A voltmeter is connected in parallel across the two points in the circuit between which you wish to measure the potential difference. It has a high resistance compared with the resistance of the rest of the circuit.

Other instruments that use a meter movement as part of their design are light-intensity meters, ohmmeters, certain meters that measure the speed of motors, and certain temperature measuring devices.

Figure 12–14 How a moving-coil galvanometer is used in various kinds of meters.

3. A meter movement with a resistance of 4.0 Ω turns through its maximum deflection when there is a current of 0.020 A. What resistance should be used to convert this meter movement into an ammeter measuring currents up to 20 A? How should the resistor be connected?

4. How can the meter movement of Problem 3 be converted to a voltmeter with a range of 30 V?

5. A permanent-magnet, moving-coil meter is designed to have a magnetic flux density between the pole faces and the core of 0.15 T. The coil consists of exactly 200½ turns of wire wound on a square form, 2.0 cm on a side. (The half-turn is necessary because the wire enters one end of the coil and leaves the other end.) What is the torque on the coil when the current in it is 1.0 milliampere?

Discussion Questions

1. Conventional current is defined as flowing from positive to negative; electron current flows from negative to positive. What is the

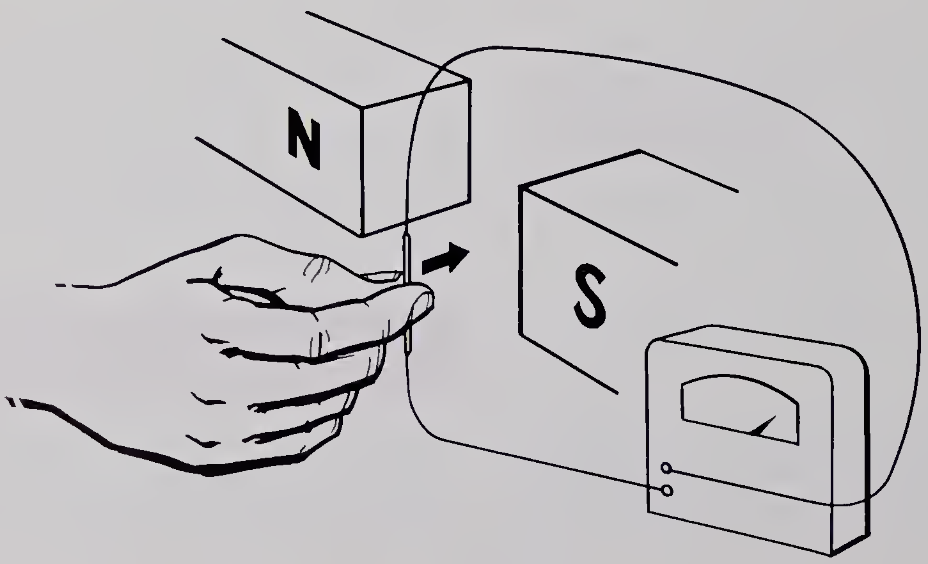
value of using the latter concept in analyzing the motor effect?

2. A century ago, experimenters did not know whether current in a wire consisted of negative charges moving in one direction, positive charges moving in the opposite direction, or both. Why could they not determine this by analyzing the direction of the motor effect?
3. Suppose you are facing a U-magnet whose S-pole is at your left and whose N-pole is at your right. If you hold a wire vertically in the field with its top connected to the positive terminal and its bottom to the negative terminal of a source of electric energy, in which direction is the resulting force?
4. What would be the result if, in Fig. 12–12, brush No. 1 were positive and brush No. 2 were negative?
5. Since current in opposite sides of a loop is in opposite directions, why do not the forces in opposite directions on the loop in the simple motor of Fig. 12–12 cancel each other?
6. Why are the armature and field windings of an electric motor usually wound on an iron core?
7. If the motor of Fig. 12–12 were supplied with ac, would it work? Why? What change in design do you recommend?

The Generator Effect

12–15 A conductor moving across a magnetic field generates an electromotive force. The student in Fig. 12–15 is conducting an experiment much like that in Fig. 12–11. Again a magnetic field is provided by a strong permanent magnet. This time, however, the student holds the wire vertically and moves it toward you and away from you, back and forth through the field. The moving wire is connected to a sensitive electric meter — a galvanometer — which indicates the existence of a feeble electric current, and hence of the electromotive force (emf) which produces the current. From this experiment, the student could observe and conclude the following:

Figure 12–15 The vertical wire is being pushed away from you, the reader. When this is done under the proper conditions, the free electrons of the wire are forced upward.



a. When the wire is moved across the magnetic field, an emf is produced.

b. When the wire is moved in a region well away from the magnet, there is no emf.

c. When the wire is moved parallel to the magnetic field, there is no emf.

d. When the wire is held stationary in a position well away from the magnet, there is no emf.

e. When the wire is held stationary in a position within the magnetic field, there is no emf.

From these observations you can conclude that the wire must be moved across the magnetic field for an emf to be generated. It is evident that the top of the wire is either positive or negative with respect to the bottom. From this you can conclude that the generated emf is at right angles to the motion and also to the magnetic field.

f. When the wire is moved across the field and away from you, an emf is produced.

g. When the wire is moved across the field and toward you, an emf is produced whose polarity is opposite to that in (f) above.

From these observations you can conclude that the direction of motion determines the direction of generated emf.

h. If the magnet's poles are reversed, the direction of the generated emf is reversed.

From this observation you can see that the direction of the generated emf is determined by the direction of the magnetic field.

i. If you vary the velocity of movement of the wire, the magnitude of the generated emf varies accordingly.

From this you can conclude that the generated emf is directly dependent on the velocity of the moving wire.

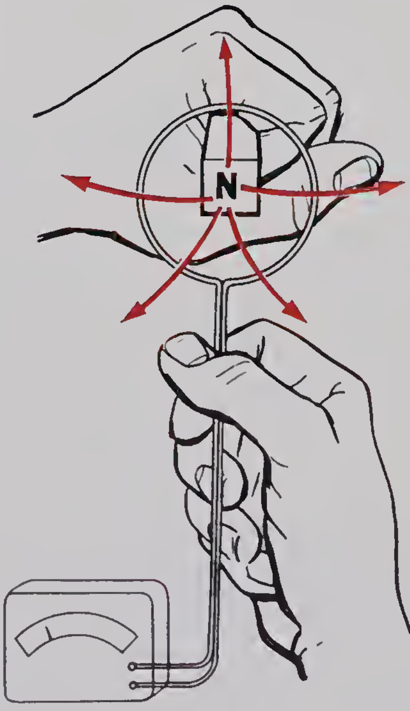
j. If you substitute weaker or stronger magnets, the magnitude of the generated emf varies accordingly.

From this you can conclude that the generated emf is directly dependent on the flux density of the magnetic field.

If you try this experiment, you may have trouble seeing the galvanometer needle move because the emf is very small; however, you can easily do the experiment in Fig. 12–16, Make a coil of wire with several turns, connect the ends to a galvanometer, and move the coil rapidly toward the N-pole of a bar magnet. The galvanometer will deflect, showing that you have produced an emf in the coil. The emf changes direction when you pull the coil away from the magnet or when you use the S-pole instead of the N-pole.

In this case, the wire in the coil which is moving in a magnetic field has most of its motion perpendicular to the field (Fig. 12–16, Accordingly you would expect

Figure 12–16 If you move a coil of wire (with at least ten turns in it) toward a magnet, a galvanometer in the circuit will deflect, showing that an emf has been produced in the coil.



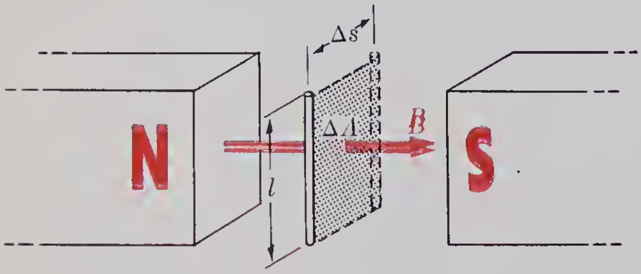
an emf to be generated. You may prefer to think of the coil this way: Through the area of the coil there is a certain amount of magnetic flux. As you move the coil toward the magnet, the amount of flux through the coil increases. Whenever the flux through a coil changes, an emf is generated.

Because the principle underlying these experiments also underlies the operation of electric generators, it is called the **generator effect**: an emf is generated in a conductor whenever the conductor moves across a magnetic field or whenever the magnetic flux changes inside a coil.

Do It Now

1. Do the experiment of Fig. 12–16, but hold the coil still and move the magnet. Does it matter whether the coil or the magnet moves? Does the flux through the coil change in both cases?
2. Suppose the wire in Fig. 12–15 were held still and the permanent magnet were moved first toward you, then away from you. What would be the result?

Figure 12–17 In this diagram a vertical conductor of length l moves away from you between the poles of a magnet. Its motion is perpendicular to the magnetic field, which is shown by the red arrow. As it moves the distance Δs, it sweeps out the area ΔA, through which the flux $\Delta\Phi$ is $B\Delta A$. The emf generated is $\Delta\Phi/\Delta t$.



12–16 The magnitude of the generated emf is easily determined. To determine the size of the generated emf, start with the equation used to define the volt (see p. 241):

$$V = \frac{\text{work}}{Q}$$

But work = Fl. Therefore:

$$V = \frac{Fl}{Q}$$

The force is caused by motion of the charge through the field and is equal to BQv. Substitute this for F:

$$V = \frac{BQvl}{Q}$$

$$V = Bvl$$

where B is the magnetic flux density in T, v is the velocity of the moving wire in m/sec, and l is the length of the moving wire in m.

This expression is completely consistent with the observations of the experiment in Fig. 12–15. Notice that this formula is for the emf generated in a conductor moving *perpendicularly* across a magnetic field.

The equation can be expressed in another way. Remember that $v = \frac{\Delta s}{\Delta t}$, where Δs is the distance the wire moves in the time Δt, as shown in Fig. 12–17. Therefore:

$$V = \frac{B(\Delta s)l}{\Delta t}$$

But $(\Delta s)l$ is the area covered by the wire in its motion, or ΔA. Thus:

$$V = \frac{B\Delta A}{\Delta t}$$

You will remember from p. 281 that B times area is the flux (Φ) through the area. Therefore $B\Delta A = \Delta\Phi$, and

$$V = \frac{\Delta\Phi}{\Delta t}$$

This formula for a generated emf is very useful for electric transformers as well as for electric generators.

12–17 The generator effect and motor effect are basically alike. The generator effect and the motor effect really are different aspects of the basic physical principle that when a charged object moves across a magnetic field, it experiences a force perpendicular to its movement and to the field. It is easy to see how this applies to the motor effect if you think of an electric current as a flow of charges (electrons). But how does the principle apply to the generator effect?

The first view of Fig. 12–18 simplifies the experiment of Fig. 12–15 by showing only a short section of the moving vertical wire. The second diagram shows a single free electron within the moving wire. Note that the electron moves away from you, just as in Fig. 12–3.

Each electron in the moving wire constitutes a tiny electric current in which the negative charge moves away from you. Each moving charge is surrounded by a magnetic field and therefore experiences a force perpendicular to its movement and to the direction of the magnetic field in which it moves. In this case, however, the deflecting force is parallel to the wire. That is, an emf is produced in the wire, and, if a complete circuit exists, there is a current in the wire.

12–18 The three-finger rule gives the direction of the generator effect. Since the motor effect and the generator effect are applications of one fundamental principle, it is not surprising that the same three-finger rule for determining direction applies in each case. Again use the left hand. In this case, the thumb represents direction of motion (movement of the wire), the index finger represents direction of magnetic field, and the middle finger represents direction of force on electrons (direction in which electrons tend to move).

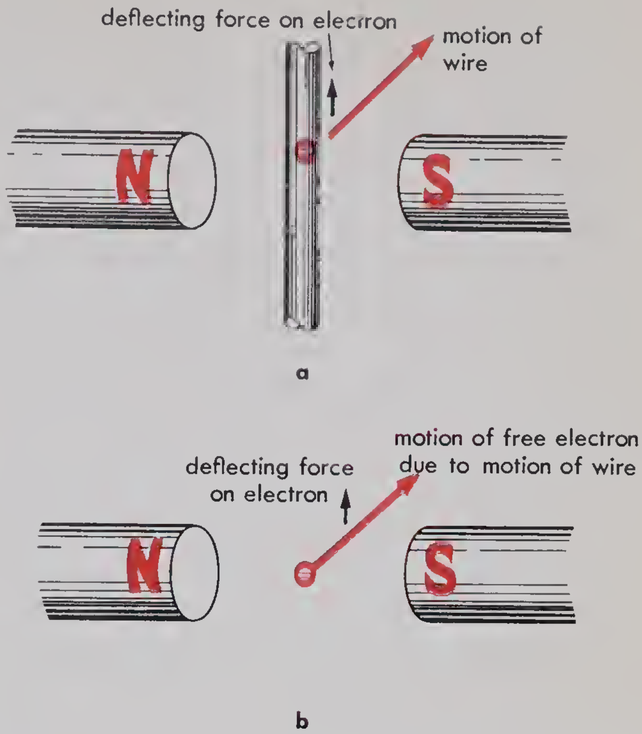

deflecting force on electron
motion of wire
N
S
a
motion of free electron due to motion of wire
deflecting force on electron
N
S
b

Figure 12–18 In **a** a vertical wire is moving away from you. Think of a single free electron in the moving wire, as illustrated in **b**. This electron is moving away from you and across the magnetic field, and hence experiences an upward force. Thus the electrons tend to crowd upward in the conductor; this creates an unequal distribution of charge in the wire — this is an emf.

Be careful in using this rule. In Fig. 12–18, if the electrons are forced upward in the wire, there tends to be an excess of electrons at the top and a deficiency of electrons at the bottom. Thus, in a circuit the wire in which the emf is generated resembles a cell with the top of the wire corresponding to the negative terminal and the bottom, the positive terminal.

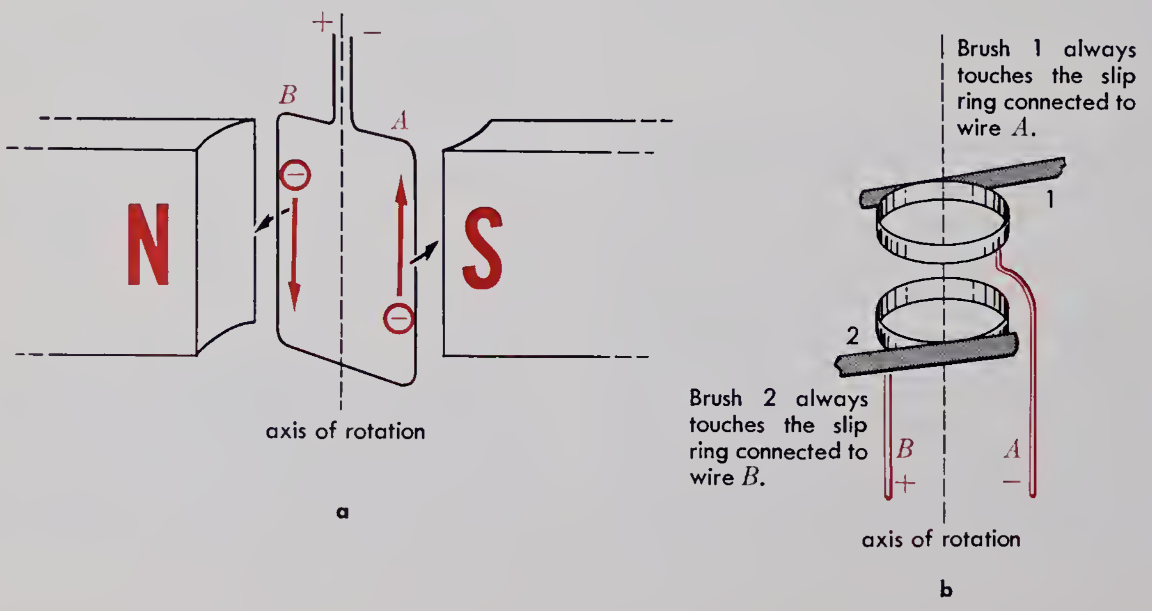
12–19 A current loop rotating in a magnetic field generates an emf. The experimenters of Figs. 12–15 and 12–16 clearly are producing electric energy. If this energy were greater, it might be useful. Evidently, the source of this energy is not the magnetic field, since that remains unchanged after the experiment is completed. The work (force × distance) provides the input energy for this generator action.

Modern electric generators are based on the arrangement shown in Fig. 12–19a. The simple loop is rotated continuously on its long axis. In the position shown, side *A* of the loop is receding; hence free electrons are forced upward. At the same time, side *B* is approaching, so its free electrons are forced downward. The two emf's support each other in forcing electrons counterclockwise around the loop, so that end *A* has an excess of electrons, while end *B* has a deficiency. Because the loop rotates continuously, means must be devised for making electric connections without twisting the wires. This is done by a pair of *slip rings* which turn with the loop and rub against a pair of stationary contact strips or brushes (Fig. 12–19b).

12–20 The alternating emf produced can be converted to a direct emf. In Fig. 12–19, it is quite evident that conductor *A* cannot always be receding and having its electrons forced upward. Actually, the direction of motion reverses every half-rotation of the loop. Careful analysis reveals also that the generated emf changes constantly in magnitude even *within* each half-revolution.

Figure 12–20 is a variation of Fig. 12–19. If the emf generated in the loop is plotted against the position of the loop, the resulting graph is as shown in Fig. 12–20b. Mathematically, this is the curve of a sine function, and the emf produced by this simple generator is said to vary **sinusoidally.** As the graph in Fig. 12–20b shows, the generated emf is changing constantly and reverses its direction every half-revolution or half-cycle. This is referred to as **alternating current (ac).** Alternating current is usable for many circuits such as those involving lamps and heating devices. Others,

Figure 12–19 **a.** The rectangular loop of wire is rotating around the axis shown by the dashed line; it is moving counterclockwise as seen from the top. Hence, electrons in *A* are forced upward; those in *B*, downward. Later, when *B* has moved over toward the right side of the picture, electrons will go up in *B*, down in *A*; the generated emf is alternating. **b.** This shows how the generated emf can be connected to an external circuit without twisting off wires *A* and *B* through continuous rotation. Section **b** of this diagram is part of **a** greatly enlarged.



Brush 1 always touches the slip ring connected to wire *A*.

Brush 2 always touches the slip ring connected to wire *B*.

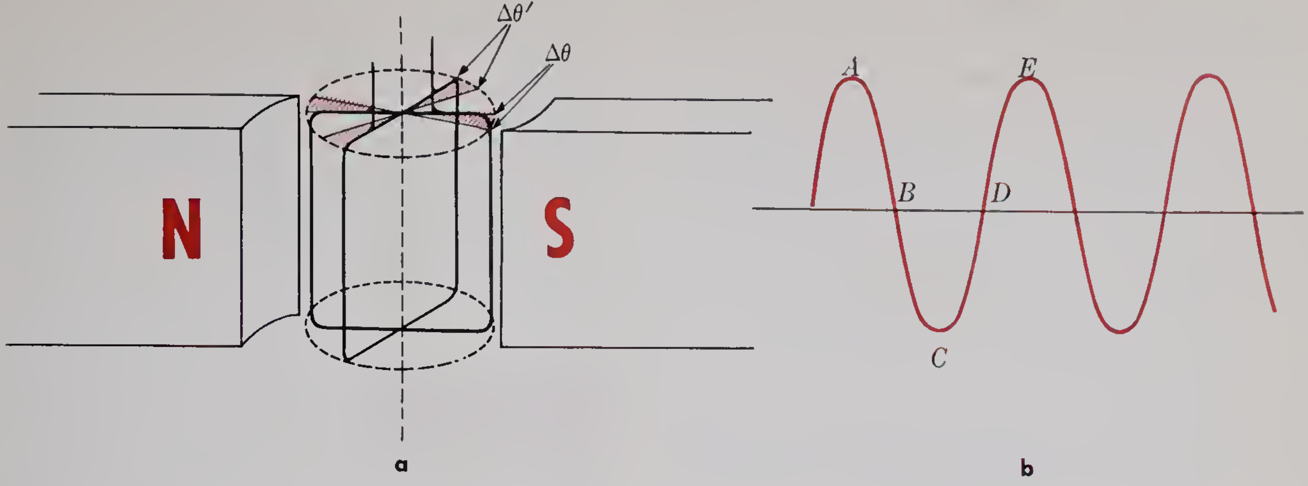


Figure 12–20 a. The two fragments of rotation $\Delta\theta$ and $\Delta\theta'$ have the same number of degrees. However, when the loop is moving through the angle $\Delta\theta$, the conductors are moving perpendicularly to the field, while at $\Delta\theta'$ they are moving in a direction that is almost parallel to it. **b.** The graph shows how the generated emf varies during the rotation. Point A represents maximum emf in one direction (for example, at $\Delta\theta$), while point C represents the maximum in the opposite direction, 180° later. One complete rotation occurs between points A and E. At points B and D the direction of rotation is parallel to the field, so the emf at those instants is zero. The emf is said to vary *sinusoidally* because the graph has the form of a sine curve.

however, require direct current, where emf and current are in one direction only.

To achieve direct current, the slip rings are replaced by a split-ring commutator like that used in the motor of Fig. 12–12. The resulting emf is graphed in Fig. 12–21.

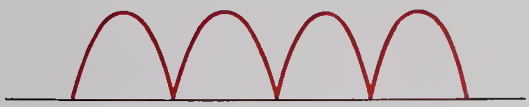


Figure 12–21 This graph shows the form of the emf produced by using a split-ring commutator instead of slip rings.

12–21 Lenz's law is a fundamental principle of electricity. In an operating electric motor the wires of the armature move across a magnetic field, as happens also in an electric generator. The fact is that an operating electric motor acts also as a generator. What is the direction of the emf produced? You can determine this from Fig. 12–12: Conductor A is moving upward. Movement is upward and field is to the right, so electrons of the generated emf are forced toward you. This is opposite in direction to the current which is causing the armature to rotate. Therefore the emf which an operating electric motor produces as a result of its own internal generator action is called its **counter emf,** or **back emf.** In motors operating normally, the back emf is nearly as great as the applied emf. Note that the emf available to run the motor is equal to applied emf minus back emf. Study Example 1 on page 298.

Counter emf illustrates a fundamental principle in electricity known as **Lenz's law:** The direction of an induced emf is such as to oppose the cause producing it.

Lenz reasoned that any electric current, including that of back or counter emf, has the ability to do work. You can see that if back emf were in the same direction as applied emf, it would actually help run the motor. Indeed, the motor might run itself and even have considerable generated electric energy left over! This, of course, would

EXAMPLE 1

A 120-V motor for a power saw is known to have an internal resistance of 1.5 Ω. While operating, it draws 12 A. What is the back emf it generates?

Given: $\text{emf}_{\text{applied}} = 120\ \text{V}$
$I = 12\ \text{A}$
$R = 1.5\ \Omega$

To find: emf_{back}

Solution: The emf available to run the motor is equal to the applied emf minus the back emf, that is:

$$\text{emf}_{\text{run}} = \text{emf}_{\text{applied}} - \text{emf}_{\text{back}}$$

or

$$\text{emf}_{\text{back}} = \text{emf}_{\text{applied}} - \text{emf}_{\text{run}}$$

Running emf is related to internal resistance by Ohm's law.

$$\text{emf}_{\text{run}} = IR$$

Therefore: $\text{emf}_{\text{back}} = \text{emf}_{\text{applied}} - IR$

$$= 120\ \text{V} - 12\ \text{A} \times 1.5\ \Omega$$
$$= 120\ \text{V} - 18\ \text{V}$$
$$= 102\ \text{V, Answer}$$

contradict the law of conservation of energy. Thus the polarity of the counter emf cannot be the same but must be the opposite of the polarity of the applied emf.

Self Check

1. How is an emf generated?
2. Suppose you have a U-shaped magnet, with the N-pole on top and the S-pole on the bottom. You hold a conductor horizontally before you and push it away from you through the gap between the poles of the magnet. Will the left or the right end of the conductor have positive electric polarity?
3. How are the generator effect and the motor effect alike?
4. Under what conditions does an electric generator need no commutator segments?
5. If a 500-V industrial motor has an internal resistance of 4 Ω and draws 20 A, what back emf does it produce?
6. State Lenz's law.

Problems

A **1.** A certain conductor generates an emf of 1 millivolt when it moves perpendicularly across a magnetic field. What emf is generated when it moves at the same speed across the same field at an angle of 45°?

2. A metal bar 8.0 cm long is dropped crosswise through a magnetic field whose flux density is 15×10^{-2} T. What is the emf between its ends if it passes through the field at a velocity of 4.0 m/sec?

3. How fast must a 30-cm bar drop through the field in Problem 2 to produce an emf of 12 V?

4. A rectangular loop 10 cm long and 6 cm wide moves from a field with a flux density of 0.20 T to one with a flux density of 0.05 T in 0.10 sec. What emf is produced? If a coil having 100 loops of this size were used, what would be the total emf?

5. A 12-V motor is known to generate a back emf of 9.0 V when operating at full speed. If its internal resistance is 1.5 Ω, what current does the motor draw when operating normally?

Discussion Questions

1. In the experiment of Fig. 12–16, what is the source of the energy which is converted into electric energy?
2. What is the advantage in looking on the generator effect as an application of the basic principle of deflecting force on a

moving charge, rather than as a separate and distinct phenomenon?

3. If somewhere in Canada a metal rod is oriented in an east-west direction and then dropped, which end of the rod will show an excess of electrons?
4. In Fig. 12–19a, one side of the loop crosses the magnetic field toward you, while the other crosses it away from you. Since one emf is up and the other down, why is the total emf in the loop not zero?
5. In a typical medium-sized electric generator, the field current may be 5 to 10 A, while the current generated in the armature may be 100 A more. Can you see why medium and large generators usually rotate the field, keeping the armature stationary?
6. Sometimes when you turn on a motor it may not start, although you know from the hum that it is supplied with current. Why should you either turn off the motor immediately or try to start it by spinning it by hand?
7. The law of conservation of energy accounts for the existence of counter emf in an electric motor. What is the corresponding phenomenon in an electric generator?

Chapter Summary

A moving electric charge may be thought of as a tiny electric current surrounded by a magnetic field. When a charge moves across another magnetic field, the two fields interact and produce a deflecting force on the moving charge which is perpendicular to the movement and also to the field in which it moves. It makes no difference whether it is the field or the charge which is moving; there must be relative motion between them. The direction of the deflecting force can be predicted from fundamental theory, or from the three-finger rule. The path of a particle moving in a direction perpendicular to a magnetic field is a circle. If the particle is not moving perpendicularly, but has a velocity component perpendicular to the field, its path is a spiral. The magnetic flux density of a field and its total flux are defined in terms of the force on a moving charge.

The ability of magnetic fields to affect the movements of charged particles underlies the operation of the mass spectrometer and the television picture tube. Magnetic fields also can focus streams of moving electrons, as in the magnetic focusing of TV picture tubes and in the capture of charged particles in the earth's magnetic field in the upper atmosphere. Magnetic fields deflect particles in cloud chambers and bubble chambers and one day may contain the intense, hot plasma of thermonuclear reactors.

A conductor carrying current across a magnetic field experiences a sideways force. This is called the motor effect and is explained by the general relation above. Here the moving charges (electrons) are trapped in the wire; hence, as they respond to the deflecting force, they move the wire with them. The force on such a wire is related to the magnetic field, the current, and the conductor length. Modern electric motors make use of this effect. The armature of a simple motor is a loop which rotates within a magnetic field. To achieve continuous rotation, the direction of current in the armature loop must be reversed every half-revolution. This is accomplished by brushes and a split-ring commutator. The rotation of dc motors can be reversed by reversing the leads of either the armature or the field. Permanent-magnet, moving-coil meter movements operate on the motor principle, but without brushes and commutator, since continuous rotation is not desired. Although such meter movements can be used to indicate almost any desired variable, they actually operate because current exists in the movable coil.

When a conductor is moved across a magnetic field, an emf is generated in the conductor. This is another illustration of the principle that a charge moving across a magnetic field experiences a lateral deflecting force. Here the deflecting force tends to move free electrons along the length of the wire, thus generating an emf. The emf produced by this generator effect is related to the magnetic field, the velocity of movement, and the length of the conductor. Modern electric generators use this principle. The emf in the armature of a generator is alternating. The construction of an electric generator is similar to that of a dc motor, and the naming of parts is essentially the same in both. A rotating electric motor operates simultaneously as an electric generator and produces a back emf. Hence, the *IR* drop in the motor itself is the difference between the applied and back emf's. This is an application of Lenz's law, which states that the direction of an induced current is such as to oppose the cause producing it. In turn, Lenz's law is a direct corollary of the law of conservation of energy.

Vocabulary

magnetic deflection (*p.* 278)
three-finger rule (*p.* 280, 295)
tesla (*p.* 281)
magnetic flux density (*p.* 280)
magnetic flux (*p.* 281)
weber (*p.* 281)
mass spectrometer (*p.* 282)
Van Allen belts (*p.* 284)
aurora borealis (*p.* 285)
plasma (*p.* 286)
motor effect (*p.* 287)
armature (*p.* 288, 289)
split-ring commutator (*p.* 288)
brush (*p.* 289)
stator (*p.* 289)
rotor (*p.* 289)
field, of motor or generator (*p.* 289)
compound-wound motor (*p.* 289)
series-wound motor (*p.* 289)
shunt-wound motor (*p.* 289)
pole faces (*p.* 289)
galvanometer (*p.* 290)
permanent-magnet, moving-coil, meter movement (*p.* 290)
generator effect (*p.* 294)
slip rings (*p.* 296)
alternating current (*p.* 296)
sinusoidal curve (*p.* 296)
Lenz's law (*p.* 297)
back (counter) emf (*p.* 297)

Problems

A

1. What is the deflecting force on an alpha particle moving at 1.0% of the speed of light directly across a magnetic field whose flux density is 0.0030 T?

2. Suppose you wish to demonstrate the deflecting force on a charged object, as in Fig. 19–2. If you have a powerful magnet which produces a flux density of 0.15 T between its pole faces and can hurl the cork between the poles at 12 m/sec, how much charge must you give to the cork for it to experience a deflecting force of 0.010 N?

3. A conductor 30 cm long weighs 20 g and is held horizontally in a vertical magnetic field whose flux density is 0.12 T. What current must be in the conductor in order for the force on the conductor to be enough to support its own weight?

4. A galvanometer with a resistance of 50 Ω has maximum deflection when the current is 400 μA. Show how to use the coil for (a) a 10-A ammeter; (b) a 100-V voltmeter.

5. At a certain spot on the earth, the horizontal component of the earth's magnetic field is 2.0×10^{-5} T. A wire oriented at right angles to the horizontal component is moved vertically with a velocity of 20 m/sec. How long must the wire be to generate an emf of 1.0 millivolt?

6. A 120-V motor with an internal resistance of 3.0 Ω draws a current of 8.0 A normally. What is the back emf?

B

7. If you wanted to write units for *B* into an equation, and wished to use only the meter, kilogram, second, and ampere (mksa system of units), what units should you use?

8. A small motor has a rotating loop consisting of 300 turns of wire in a rectangle whose ends are 6.0 cm and whose sides are 12.0 cm. The armature draws 4 A of current while the long sides of the loop are across a field whose flux density is 0.12 T. What is the torque on the armature?

Discussion Questions

1. What is the function of the magnetic field surrounding a bubble chamber such as that on page 276?
2. From what direction must charged particles approach the earth in order to be unaffected by its magnetic field?
3. What three things must be present before there can be a motor effect?
4. How would you have to arrange an electric motor so that it could do useful work?
5. In a permanent-magnet, moving-coil electric meter, how is the coil (armature) given the benefit of an iron core without making it extremely heavy?
6. What is the source of the energy that is converted to electric energy in a generator?
7. Two coils of wire, each mounted on a separate shaft, can be rotated in a magnetic field. All conditions are alike for the two coils and shafts, except that the two ends of one coil are left apart, while the two ends of the other are soldered together. Which coil is harder to turn? Why?

CHAPTER 13

Black Star

Almost all electric energy sold today is in the form of alternating current, because only alternating current can be transmitted great distances without large losses due to heating of the wires.

Alternating Current

In the early 1880's North American Cities at night looked far different from today. Streets and homes were usually lit by gas or oil lamps. Within the preceding few years, Edison had demonstrated the practical incandescent lamp. However, there there were no public electric power systems although there were some cities festooned with myriads of electric wires for telephone and telegraph circuits.

The first commercial electric power system, developed by Thomas Edison, was strictly a direct current system. Most scientists were convinced that alternating current was neither safe nor practical for commercial use, and that it had no compensating advantages. When you consider that practical distribution of electric power started with direct current, and that dc systems predominated for many years, it is surprising that ac ever came into its own. Today, however, electric power systems are based almost exclusively on alternating currents. Evidently there are some features of alternating-current electricity which make it particularly valuable in modern commercial situations.

In this chapter you will learn about the characteristics of alternating-current and some special applications of this type of electric energy.

Characteristics of Alternating Current Circuits

13-1 Potential difference and current both vary sinusoidally. In Fig. 12–19 you studied a simple electric generator. You saw that when a loop of wire rotates in a uniform magnetic field, the magnitude of the generated emf varies sinusoidally. When this simple generator is equipped with a split-ring commutator and a set of brushes, the current is direct, that is, in one direction only, even though in so simple a generator it is not constant in amplitude. However, if the generator is built with the slip rings of Fig. 12–19b, the output is sinusoidal in pattern and it is alternating current.

It is important to realize that in a simple ac circuit, both the emf which appears across the generator terminals and the current which it produces vary sinusoidally. In dc circuits, you have been using the symbol I to represent the steady value of the current. In ac circuits, where the magnitude of the current varies all the time, the symbol i is used for the instantaneous value of the current. $I_{\max}$ is then used for the maximum value of the current. The equation of an alternating current is:

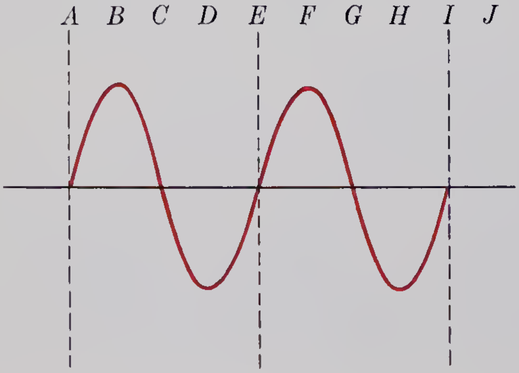
$$i = I_{\max} \sin \theta$$

where θ (*theta*) is called the **phase angle.** In a simple generator, as in Fig. 12–19, the phase angle is the position angle of the rotating loop; θ is 0 when the loop is perpendicular to the field.

13–2 The most common commercial ac frequency is 60 cycles per second. Figure 13–1 shows a sine curve. The interval between A and E is one complete cycle; from B to F is also one cycle. An alternating current can be characterized by its **frequency,** the number of complete cycles it has each second.

The overwhelming majority of commercial ac circuits involve emf's and currents which have 60 cycles per second (cps).

Figure 13–1 This is the diagram of a sine function: $y = k \sin x$. The wave form is sinusoidal; it is often called a sine wave. It is important to realize that the wave form of alternating current is actually a sine wave. The sine wave has one complete cycle in the interval of time between A and E and also between B and F. The wave form changes polarity *twice* during each complete cycle.



This is commonly referred to as 60-cycle ac. In a few places 25-cycle, 30-cycle, or 50-cycle current is used.

Commercial electric power stations maintain their frequencies amazingly close to exactly 60 cps. Although frequencies may vary slightly from one minute to the next, their daily average is for all practical purposes exact. The dependability of commercial power frequencies permits the constant-speed operation of many motors. In particular, electric clocks can be synchronized so they can keep time without significant error.

Do It Now

Obtain a simple, two-electrode, neon-type lamp which can be screwed into a household electric socket. Mount it on a flexible power cord and move it briskly back and forth while it glows. Can you see evidence that the lamp is really flickering? Can you tell that first one plate glows, then the other? What does this suggest to you?

13–3 Quantities of ac are measured in effective values. What meaning can measurement of alternating emf and current have when these values are constantly changing? A moment's thought shows that the actual mathematical average of sinusoidal values is 0. At first it is confusing to think that in an ac circuit electrons move merely back and forth without ever getting anywhere. Yet regardless of the direction in which electrons move in a resistor, they always deliver energy to it, and this energy appears as heat. Therefore, 1 ampere in an alternating circuit (**ac ampere**) is defined as that current which produces the same heating effect in a given resistor as does 1 dc ampere.

An alternating current with a maximum value of 1 ampere will not produce as much heat as a direct current with a value of 1 ampere. It has been found that the **effective value** of an alternating current (I_{eff}) is 0.707 times its maximum value (I_{max}):

$$I_{\text{eff}} = 0.707\ I_{\text{max}}$$

Similarly:

$$V_{\text{eff}} = 0.707\ V_{\text{max}}$$

The effective value of a current or of an emf is also called the **root-mean-square** (rms) value; the reason for this latter name is obvious if you follow the proof given in the next section.

13–4 The equation for the effective value of an alternating current can be derived. The rate at which heat is produced in a resistor is the power output of the resistor; this rate in an ac circuit is compared with the performance of a dc circuit.

Figure 13–2 graphs the alternating current and also the power in a 3-Ω resistor when the maximum current is 1 ampere. Notice that the power is never negative. (Power = i^2R, and the square of a negative i is positive.)

A line has been drawn halfway up the power curve, dividing it into two. You can see by inspection that the upper half has the same shape as the lower. Therefore, this halfway line represents the average power. (Actually you ought not to rely on inspection for this conclusion, but advanced mathematics is required to prove that it is true.) For an ac circuit:

$$P = \tfrac{1}{2}P_{\text{max}} = \tfrac{1}{2}(I_{\text{max}})^2R$$

If the same resistance (R) exists in a dc circuit, the power is:

$$P = I^2R$$

If the dc circuit is producing the same power as the ac circuit, then the right-hand sides of these equations are also equal:

$$I^2R = \tfrac{1}{2}(I_{\text{max}})^2R$$

Solving for I:

$$I = \sqrt{\frac{(I_{\text{max}})^2}{2}}$$

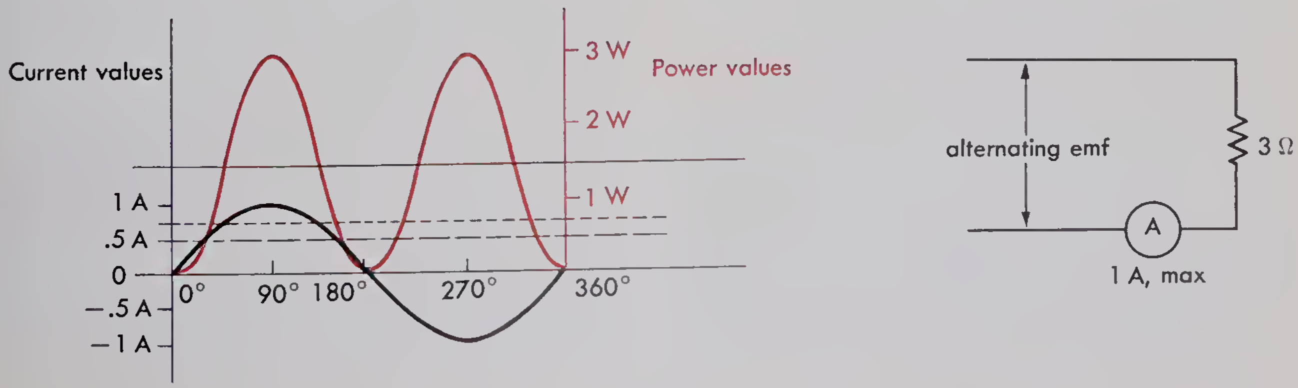
$$= \frac{I_{\text{max}}}{\sqrt{2}}$$

$$= 0.707\ I_{\text{max}}$$

What this means is that a direct current with a value of 0.707 of the maximum value of an alternating current has the same power output or heating effect as the alternating current. Therefore, 0.707 I_{max} is the effective value of the alternating current.

Although the graph in Fig. 13–2 is obtained by using a particular circuit (with a maximum current of 1 ampere and a 3-Ω resistor), the result would be the same for any values of I_{max} and R.

Figure 13–2 This set of graphs compares current and power in the ac circuit shown at the right.



13-5 Ohm's law applies to purely resistive circuits. A circuit which contains only resistance in the load is said to be purely resistive. In such a circuit, Ohm's law can be used regardless of whether the current is ac or dc. In ac circuits, when the formula $I = V/R$ is used, the values for I and V must correspond. If I is $I_{\max}$, then V must be $V_{\max}$. If effective, or rms, values are used for current, they must also be used for V. When you want to be specific, you designate maximum values as $I_{\max}$ or $V_{\max}$ and effective values with the subscript $_{\text{eff}}$. When no subscript is used, the values for I or V are effective values. See Example 1.

EXAMPLE 1

A 120-volt supply is used to operate a bathroom heater (a purely resistive load) which has 15.0-Ω resistance. What is the maximum instantaneous value of the current in the heater?

Given: $V_{\text{eff}} = 120$ V
$R = 15.0\Omega$

To find: $I_{\max}$

Solution:

$$\begin{aligned} I_{\text{eff}} &= V_{\text{eff}}/R \\ &= 120\text{ V}/15.0\Omega \\ &= 8.00\text{ A} \\ I_{\text{eff}} &= 0.707 I_{\max} \\ I_{\max} &= I_{\text{eff}}/0.707 \\ &= 8.00\text{ A}/0.707 \\ &= 11.3\text{ A, Answer} \end{aligned}$$

(Or, the problem could be done by first converting the 120 V_{eff} to maximum values, then applying Ohm's law using maximum values throughout.)

13-6 Ac measurements require special instruments. From what you learned about permanent-magnet, moving-coil movements in Chapter 12, you can see that such a device would be of no value for ac measurements. The movement would simply average out the sinusoidal current and indicate 0, although the needle might quiver a bit about the 0-point on the scale.

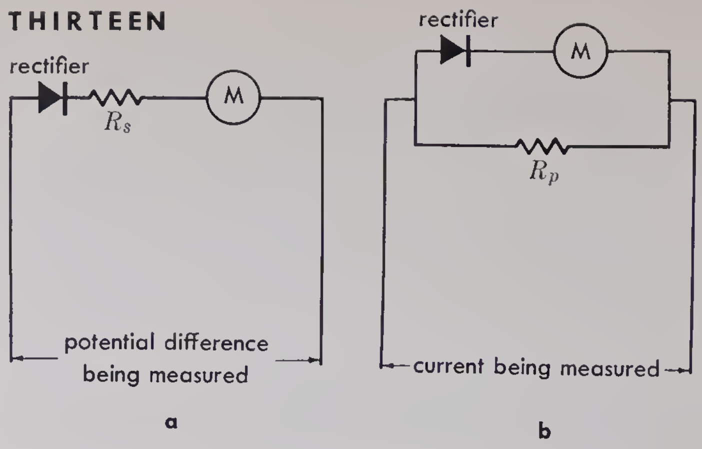


Figure 13–3 Permanent-magnet, moving-coil meter movements can be used to measure ac values by using a rectifier unit as shown above. The rectifier unit permits electrons to move in one direction only. The values of the series resistor R_s and the parallel resistor R_p are different from those in the corresponding dc instrument.

One way to measure ac values is to use a permanent-magnet, moving-coil movement in conjunction with a **rectifier**, a device which permits electrons to flow through it in one direction only. When used as in Fig. 13–3, the meter movement averages only the positive (or negative) half of the sinusoidal wave-forms; hence its deflection is proportional to the magnitude of current in the circuit.

Figure 13–4 shows a different kind of meter movement which is particularly useful in ac circuits. When the meter is in use, current exists in the coil. The current magnetizes the two soft-iron plates or vanes inside it. Regardless of current direction, the two vanes are *magnetized* alike. As a result, they repel each other. The greater the current in the coil, the greater is the force of repulsion, hence the farther apart the vanes are forced. Either of these meter movements can be used in ac circuits to measure potential difference or current by using a multiplier or a shunt, as you learned in Chapter 12.

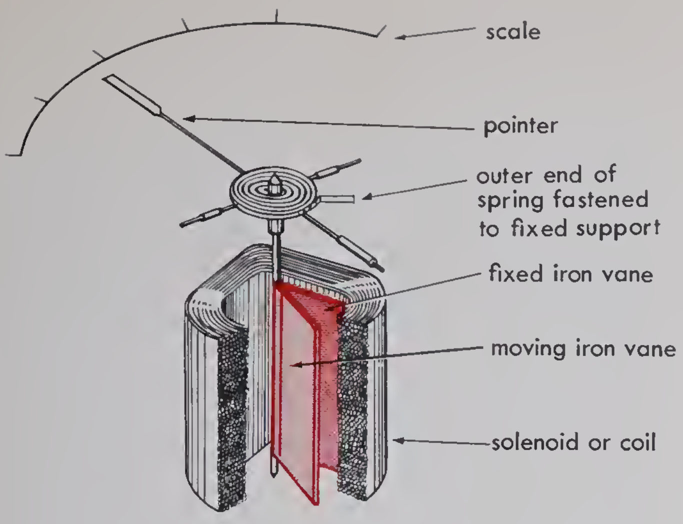


Figure 13–4 In this meter movement both iron vanes are magnetized alike, regardless of the polarity or the wave form of the magnetizing current. The greater the average current, the stronger are the magnets; therefore, the more they repel.

Self Check

1. Describe the manner in which alternating current alternates.
2. What is the duration of one cycle of alternations in 60-cycle ac?
3. How many times each second does the potential difference between the leads of a 60-cycle power cord reverse itself?
4. Why cannot the effective value of a sinusoidally varying alternating current be simply the average of instantaneous values throughout a single complete cycle?
5. How is a 1-A alternating current defined?
6. What is the effective value of an alternating current with an instantaneous maximum of 10.0 amperes?
7. What is the maximum instantaneous value of an emf if the effective value is 100 volts?

Problems

A **1.** Use the table of trigonometric functions on p. 409 to plot the graph of an ac when $I_{max} = 10$ A. Plot horizontally (as abscissa) the magnitude of angle from 0° to 720° in intervals of 15°. For each angle, plot vertically (as ordinate) the value of the instantaneous current. Are there any segments of the curve which seem to be a straight line? After what interval does the curve repeat itself? At what phase angles does $i = 0$? At what phase angles is i a negative maximum?

2. A given ac generator supplies current whose instantaneous maximum is 40 A. What is the effective value of this current?

3. What is the maximum instantaneous potential difference between the wires of an ac supply rated at 120 V?

4. A special voltmeter which registers maximum values of potential difference indicates that V_{max} across a 400-Ω resistor is 100 V. What power is represented by the heat developed in the resistor?

5. A pair of insulated wires to be used for a 120-V ac power cord are tested for insulation strength. The insulation does not break down even when the potential difference between the wires is supplied by a 150-V battery. Would such insulation be safe for the purpose indicated? Explain.

B **6.** A 1000-cycle ac circuit carries 12 A. What is the maximum instantaneous current? What is the instantaneous current 0.25 millisec after the current rises through 0? 0.75 millisec after the current rises through 0? 0.125 millisec after the current rises through 0? 0.833 millisec after the current rises through 0?

Discussion Questions

1. A permanent-magnet, moving-coil meter movement of 5-V full-scale reading is used to measure a 120-V ac potential difference. Although the needle of the instrument barely moves, its winding burns out in 2 or 3 sec. How could the meter be damaged without its needle even moving?
2. Why are effective values more meaningful than maximum values in describing the magnitude of alternating potential difference or current?

Capacitors and Inductors

13–7 Electrons flow into and out of a capacitor. You have already learned that a capacitor consists of two conductors separated by a nonconducting material. You also know that the unit of capacitance is defined by the relationship $C = Q/V$, where C is the capacitance in farads, Q the quantity of stored electric charge in coulombs, and V the potential difference between the plates, measured in volts.

Electrons flow into and out of capacitors, but not through them. In Fig. 13–5a, for example, when the switch is closed as shown, electrons flow into plate *A* and out of plate *B*. As plate *A* becomes negative, it repels electrons out of plate *B*; and as plate *B* becomes positive, it attracts more electrons into plate *A*. While the capacitor is being charged, electrons flow in the wires of the circuit. Although no electrons flow *through* the capacitor, a current does exist for a short time in the remainder of the circuit. As soon as the capacitor is fully charged, current ceases. Current exists again briefly whenever the capacitor is discharged.

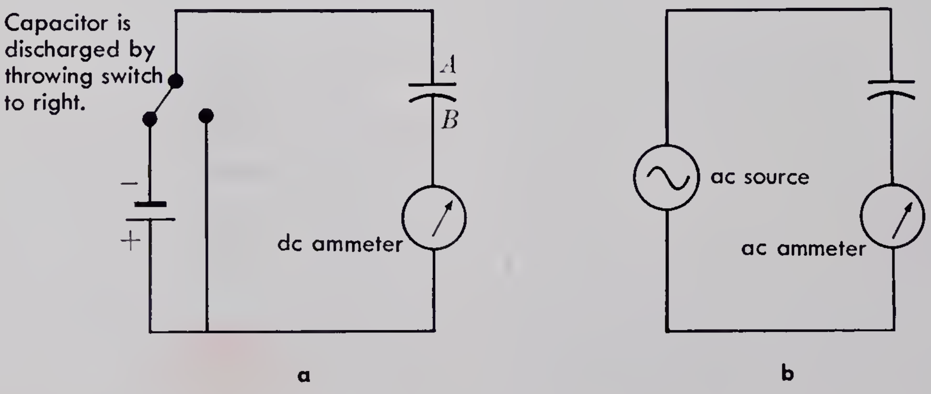
What happens when a capacitor is part of an ac circuit, as in Fig. 13–5b? Remember that current exists in Fig. 13–5a only when the capacitor is charging or discharging. This occurs in the brief interval after the potential difference changes, as when the switch is closed. But in the ac circuit the potential difference between capacitor plates is *constantly* changing. Hence a current of some kind must exist in the circuit at all times, first a surge of electrons into one plate, then into the other.

Do It Now

A large capacitor is connected in series with a 120-volt lamp bulb and to a 60-cycle household source of electric energy. Why does the lamp glow, even though no electrons flow through the capacitor?

13–8 Capacitors present opposition to alternating current. In a circuit such as that of Fig. 13–5b, two factors affect the magnitude of the current. One is the size of the

Figure 13–5 **a.** In this circuit, current is indicated by the meter for a brief interval after the capacitor starts to charge and for a brief interval after it starts to discharge. **b.** In this circuit, the applied potential difference is alternating; therefore, the ammeter in the circuit indicates current virtually at all times. Notice the symbol for a source of alternating potential difference.



capacitor: the greater its capacitance, the more charge flows into it and out of it, other things being equal. The other is the frequency of current alternations: the higher the frequency, the more often the capacitor charges and discharges, hence the greater the total electron flow in the circuit. Thus, large capacitance and high frequency permit a larger current in an ac circuit.

It is useful to state this relationship in terms of current restrictions, much as resistance restricts currents in a dc circuit. From the above you can see that the ability of a capacitor to limit current in an ac circuit varies inversely both with capacitance and with frequency. This limiting ability is called **capacitive reactance** and is represented by the symbol X_C. The reactance of a capacitor is given by the formula:

$$X_C = \frac{1}{2\pi fC}$$

where X_C is capacitive reactance in ohms, f is frequency in cycles per second, and C is capacitance in farads. This formula applies only to sinusoidal ac.

In a purely capacitive circuit — one with only capacitance in the load — the current is inversely proportional to reactance, an exact counterpart of Ohm's law.

$$I = \frac{V}{X_C}$$

where I is in amperes, V is in volts, and X_C is the capacitive reactance in ohms. Study Example 2.

13–9 Current and potential difference do not coincide in a capacitor.

In most of the circuits analyzed so far, the loads have contained nothing but electric resistance, and changes in potential difference have been instantaneously accompanied by corresponding changes in current. Is this true also of circuits which contain capacitance?

EXAMPLE 2

What effective current exists in an ac circuit containing a 12.0-μF capacitor when connected to a source of 300 volts at 60.0 cps?

Given: $C = 12.0\ \mu\text{F} = 12.0 \times 10^{-6}\ \text{F}$
$f = 60.0\ \text{cps}$
$V = 300\ \text{V}$

To find: I

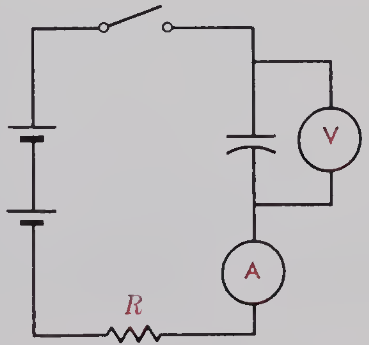
Solution: $I = V/X_C$ and $X_C = 1/2\pi fC$

By substitution:

$$I = V \times 2\pi fC$$
$$= 300\text{V} \times 2\pi \times 60.0\,\text{cps} \times 12.0 \times 10^{-6}\ \text{F}$$
$$= 1.36\ \text{A, Answer}$$

In Fig. 13–6 when the capacitor is just beginning to charge, the potential difference across it is very low, but electrons flow rapidly into it, creating a large current. As the charge accumulates in the capacitor, the potential difference across its plates increases. However, the large charge repels electrons and therefore the current decreases. Consequently, current is at a maximum *before* the potential difference between the plates reaches a maximum. Ac-

Figure 13–6 This circuit shows a capacitor that can be charged from a battery. An ammeter and a voltmeter permit measurement of current and of potential difference. The resistance in the circuit is shown because all circuits have some resistance.



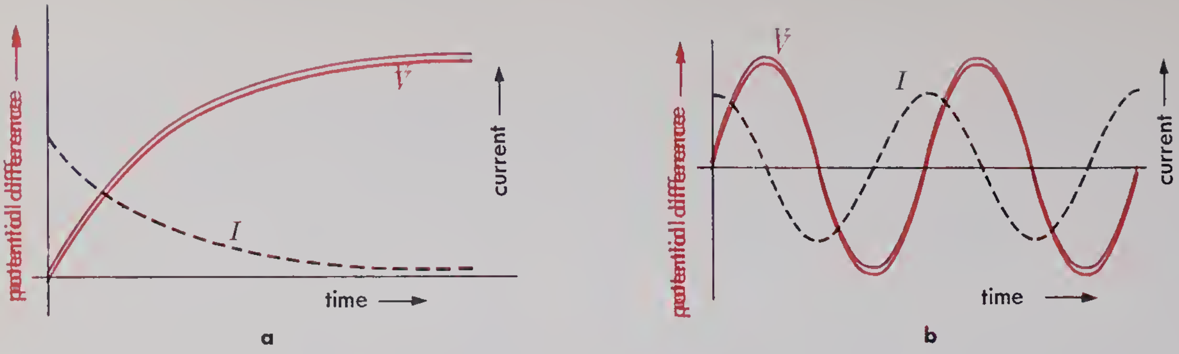


Figure 13–7 **a.** This graph shows the relationship between potential-difference variations and current variations in the circuit of Fig. 13–6. **b.** This graph shows the relationships between the potential-difference variations and the current variations in a capacitor in an ac circuit. Notice on the graphs that the solid line (V) represents the potential difference and that the dashed line (I) represents the current.

tually, as Fig. 13–7a shows, current is maximum when the potential difference across the capacitor plates is 0 (at the instant when charge begins to flow), and current is 0 when the potential difference across the capacitor plates is maximum (when the capacitor is fully charged).

If an ac source is substituted for the battery in Fig. 13–6, the capacitor alternately charges and discharges. Because the current is at its maximum before the potential difference reaches its maximum, it is common to say that current *leads* potential difference in a capacitor (Fig. 13–7b). Notice that the two sine-waves are displaced by a quarter of a complete cycle, that is, by 90°. This is called the **phase difference** between current and potential difference.

13–10 Lenz's law applies to a loop of wire. In the preceding chapter a very important principle of electricity, Lenz's law, was developed. It was used to explain the existence of back emf in motors, and the need for mechanical work to turn the rotor in generators. To see how Lenz's law applies also to a loop of wire, it is restated here in a modified form.

> *When an emf is induced in a conductor, the resulting events are such as to oppose the cause of the induced emf.*

In Fig. 13–8 a current in the loop produces a magnetic field along the loop's axis. When the current increases, the flux density increases. This changes the total flux through the coil. Hence, according to the generator effect, an emf is induced in the loop of wire. By Lenz's law, the direction of the induced emf is such that it opposes an increase in current. In a similar way, a decreasing current produces a decrease in flux which also induces an emf in the loop. The direction of this induced emf is such as to oppose the decrease of current; that is, it tends to sustain the current, an effect known as **self-induction**.

Self-induction of a coil of conductors is increased if the turns are tightly coiled, if there are many turns, and if there is a core of high relative permeability. A straight wire in a vacuum has a minimum of self-induction, although it is not zero. The self-inductive effect of simple connecting wires is usually ignored.

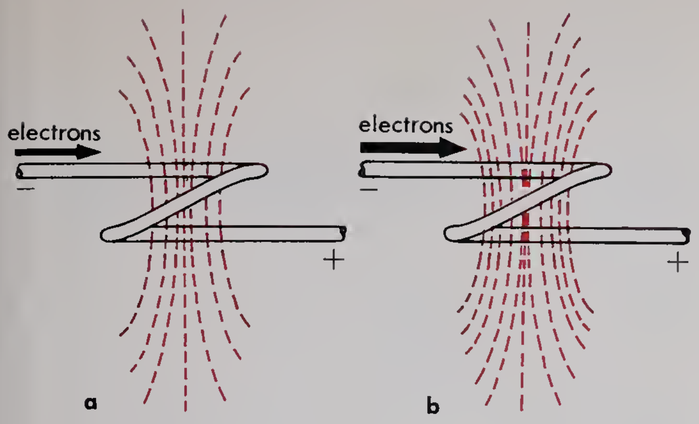


Figure 13–8 a. A loop of wire has moderate current and a corresponding magnetic field. b. The current has increased, thus increasing the total flux throughout the loop. As a result, an emf is induced in the loop.

Do It Now

1. Suppose that a coil of wire has a soft iron core. Soft iron is easily magnetized when current exists in the coil and easily demagnetized when the current ceases. Given the same change in current in both cases, compare the self-induced emf of this coil with its self-induced emf if it had no core.
2. In Fig. 13–8, if an increasing current exists from left to right in the wire, what is the direction of the induced emf? What would be its direction if the current changed direction?

13–11 An induced emf is proportional to rate of change of flux. When an emf is induced by a change in flux, the greater the change and the faster it happens, the greater the induced emf. Expressed mathematically:

$$V = \frac{\Delta\Phi}{\Delta t}$$

where V represents the induced emf and $\Delta\Phi$ represents the change of flux in the loop of wire during the time Δt. $\Delta\Phi$ must be expressed in webers and Δt in seconds; then V is in volts. The proof of this relationship is given in Sec. 12–16.

A coil of wire rarely has only one loop. If it has several loops, or *turns*, an emf is induced in each loop; since the loops are in series, the emf's can be added. Therefore, for a coil:

$$V = N\frac{\Delta\Phi}{\Delta t}$$

where N is the number of turns in the coil.

13–12 Self-inductance is measured in henries. The ability of a coil to produce a self-induced emf is measured by a quantity called **self-inductance**. The coil is called a self-inductor or, more commonly, simply an **inductor**. The unit of self-inductance is the **henry (H)**, named in honor of Joseph Henry, the American teacher-scientist who did much pioneer work on electromagnetism.

Remember that inductance occurs because a change of current in a loop induces an emf in the conductor of which the loop is made. Accordingly, the henry is defined in terms of the emf induced by a unit rate of change of current. An inductor has a self-inductance of 1 H if a rate of change of current of 1 ampere/sec induces an emf of 1 volt. Expressed mathematically:

$$V = L\frac{\Delta I}{\Delta t}$$

where V is induced emf in volts, L is inductance in henries, ΔI is change of current in amperes, and Δt is the corresponding interval of time.

The inductance of a coil is increased if the coil has more turns and if the core is iron instead of air. Inductance is also influenced by the shape of the coil. Inductors exist in many shapes and sizes. Some have iron cores and some do not. In practice, inductors are often referred to as **choke coils** or **chokes** or **coils**.

13–13 Inductors present opposition to alternating current. The action of an inductor is such as to oppose any change in current (Lenz's law). Since alternating current is constantly changing, an inductor constantly opposes it, and therefore restricts the current in an ac circuit.

The greater the inductance, the greater is the restricting effect. Again, since high-frequency currents change more rapidly than low-frequency currents, the greater the frequency, the greater is the restricting effect. Thus the ability of an inductor to restrict current varies directly both with inductance and frequency.

This opposition to current, as in the related case of capacitors, is called reactance. **Inductive reactance** can be defined as the ability of an inductor to restrict current in an ac circuit. It is represented by the symbol X_L.

The reactance of an inductor is given by the formula:

$$X_L = 2\pi f L$$

where X_L is the inductive reactance in ohms, f is the frequency in cycles/sec, and L is the inductance in henries. This formula applies only to sinusoidal ac.

In a purely inductive circuit, X_L can be substituted for R in Ohm's law; that is,

$$I = \frac{V}{X_L}$$

where I is in amperes, V is in volts, and X_L is the inductive reactance in ohms. Study Example 3.

EXAMPLE 3

What current exists in a circuit containing a 15.0-H coil when connected to a source of 300 volts rms at 60.0 cps?

Given: $L = 15.0$ H
$f = 60.0$ cps
$V = 300$ V rms

To find: I

Solution: $I = V/X_L$ and $X_L = 2\pi f L$

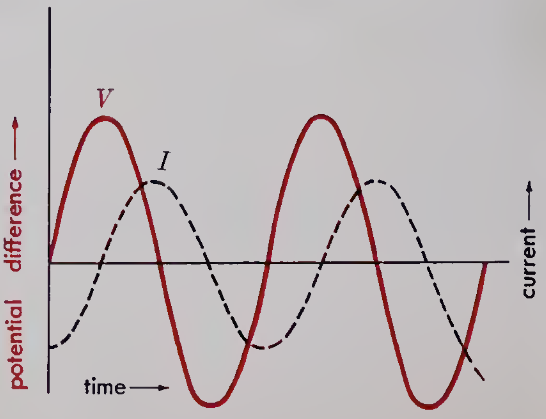
By substitution: $I = V/2\pi f L$

$$\frac{300 \text{ V}}{2\pi \times 60.0 \text{ cps} \times 15.0 \text{ H}} = .0531 \text{ A}$$

Answer

13–14 Current and potential difference do not coincide in an inductor. You already know that changes in potential difference and current do not coincide in a capacitor. The same is true in an inductor,

Figure 13–9 This graph shows the relationship between current and potential difference for an inductor in an ac circuit. Notice that the current is maximum when the potential difference is 0, and that the potential difference is maximum when the current is 0. The current in the inductor reaches its maximum a quarter of a cycle later than the time when the potential difference in the inductor reaches its maximum. Thus the current lags the potential difference by 90°. Because the current continues to change sinusoidally, the induced emf also continues to change sinusoidally.



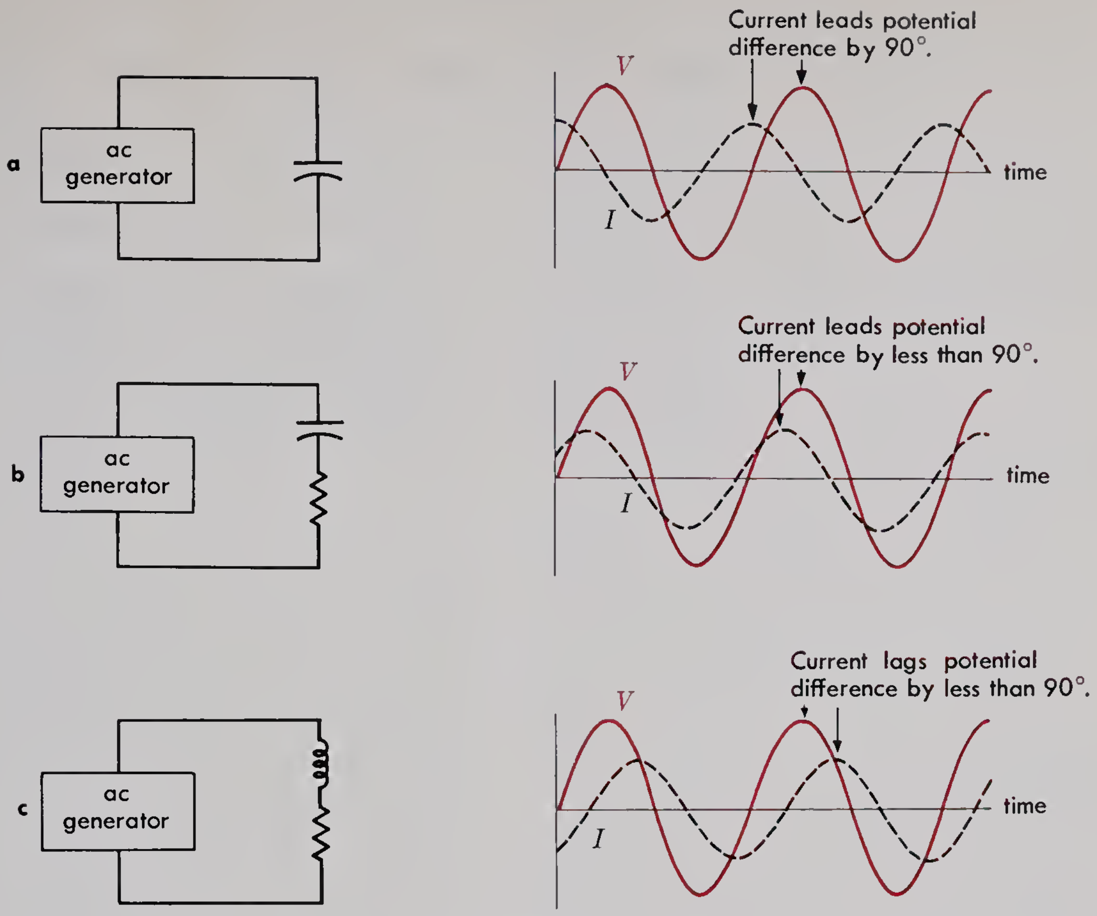

a
ac generator
V
I
time
Current leads potential difference by 90°.
b
ac generator
V
I
time
Current leads potential difference by less than 90°.
c
ac generator
V
I
time
Current lags potential difference by less than 90°.

Figure 13–10 These three circuits illustrate possible relationships between potential difference and current in typical circuits. **a.** This circuit is purely capacitive. The current in the load — and therefore that in the generator — leads potential difference by 90°. **b.** Generator current leads potential difference by less than 90°. **c.** Current lags potential difference by less than 90°.

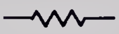
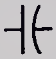
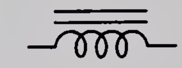
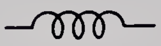
although in that instance the relationship is different.

When an alternating potential difference is increasing between the terminals of an inductor, the reaction opposes the increase of current. But when the potential difference decreases, the reaction helps the current to continue. Therefore, when the potential difference has reached its maximum value and has begun to decrease, the current continues to increase for a brief interval. Thus the current peak comes *after* the potential difference peak; that is, the current *lags* the potential difference. Figure 13–9 illustrates the relationship. Notice that in a pure inductor, current lags the potential difference by 90°.

13–15 Some circuits involve reactance and resistance. The circuit in Fig. 13–10a is purely capacitive. However, the circuits in Figs. 13–10b and c are more realistic, since in reality there are no circuits which have zero resistance. Since the phase difference in a resistor is 0°, the effect of the resistance in the circuit is to make the phase difference of the circuit as a whole less than 90°. The graphs show how the presence of resistance changes the phase difference.

When the load in a circuit is partly due to resistance and partly due to reactance, it is said to have **impedance**, represented by the letter Z. Although both resistance and reactance are measured in ohms, you can-

Table 1 TERMS AND SYMBOLS IN AC CIRCUITS

	resistive	*capacitive*	*inductive*
Object	resistor	capacitor	inductor
Common names for the object	resistor, resistance wires, heating element	capacitor (improperly but commonly called condenser)	inductor, choke, choke coil, coil
Symbol for the object			 with iron core  with no iron core
Characteristic property of the object	resistance	capacitance	inductance
Symbol for characteristic property	R	C	L
Unit in which characteristic property is measured	ohm	farad	henry
Symbol for unit of measurement	Ω	F	H
Opposition which object presents to ac	resistance	capacitive reactance	inductive reactance
Formula	R	$X_C = \frac{1}{2\pi fC}$	$X_L = 2\pi fL$
Unit in which resistance and reactance are measured	ohm	ohm	ohm

not simply add them to find the impedance because the potential differences all make different angles with the current. In general, the impedance of a series circuit is given by the equation:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

The impedance is expressed in ohms, and the current in the circuit is given by:

$$I = \frac{V}{Z}$$

Table 1 summarizes the vocabulary and terms used in ac circuits.

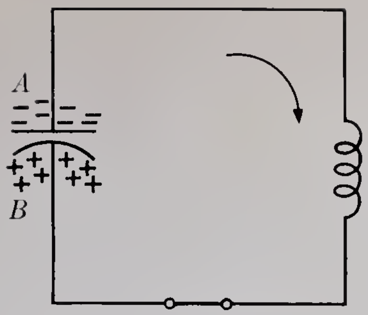


Figure 13–11 This circuit consists of an inductor and a capacitor. If the capacitor is charged and the switch closed, electrons will flow (arrow) from A to B through the inductor. Eventually the process is reversed, and thus the circuit is said to oscillate.

13–16 A circuit with capacitance and inductance is a resonant circuit. The circuit of Fig. 13–11 consists of an inductor and a capacitor. Suppose that somehow the capacitor has been charged and you close the switch. Electrons immediately tend to flow away from plate A, through the inductor, and toward plate B. However, the self-inductance of the inductor prevents an abrupt rise of current. Instead, the current rises gradually. As the current drains the charge from the capacitor, the potential difference across its plates decreases. Presently the charge in the capacitor is reduced to zero, but by now there is a considerable current in the inductor. Now the self inductance tends to maintain this current, so the capacitor begins to charge with polarity opposite to that which it originally possessed. As the capacitor becomes increasingly charged, it opposes additional electron flow more and more. Thus by the time the current has been reduced to zero, the capacitor has approximately as much charge as it had when you closed the switch, except that it is in reversed polarity.

Now the capacitor starts to discharge again, with electrons streaming away from B. The whole chain of events is repeated in the opposite direction. The circuit is said to oscillate, and this type of circuit, containing both capacitance and inductance, is called an **oscillating**, or **resonant**, **circuit**.

A charged capacitor possesses energy. As it loses its charge, the energy is transferred to the inductor, which stores it in its magnetic field. In an oscillating circuit, the energy is passed back and forth from capacitor to inductor to capacitor. If there is resistance in the circuit, a bit of the energy is lost as heat (I^2Rt), and the oscillations die out.

An oscillating circuit is very much like a pendulum. In a pendulum, energy is transferred from potential at one end of the swing to kinetic at the mid-point and back to potential at the other end of the swing. In an oscillating circuit, the energy is transferred from an electric field (between the plates of the capacitor) to a magnetic field (within the inductor) and back.

An oscillating circuit is like a pendulum in another way. The oscillations have a natural frequency, which is determined by the capacitance and inductance of the circuit. This natural period of oscillation of a resonant circuit is called its **resonant frequency** (f_r); it is the frequency that makes the two reactances equal in magnitude. That is:

$$X_L = X_C$$

$$2\pi f_r L = \frac{1}{2\pi f_r C}$$

Solving for f_r:

$$f_r^2 = \frac{1}{2\pi L \times 2\pi C}$$

$$= \frac{1}{4\pi^2 LC}$$

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

Note that f_r is in cycles per second, L is in henries, and C is in farads. See Example 4 on p. 316.

EXAMPLE 4

What is the resonant frequency of a circuit containing a capacitor of 12 μF and an inductor of 6.0 H?

Given: $C = 12\ \mu\text{F} = 12 \times 10^{-6}\ \text{F}$
$L = 6.0\ \text{H}$

To find: f_r

Solution:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{6.0 \times 12 \times 10^{-6}}}$$

$$= \frac{1}{2\pi\sqrt{72 \times 10^{-6}}}$$

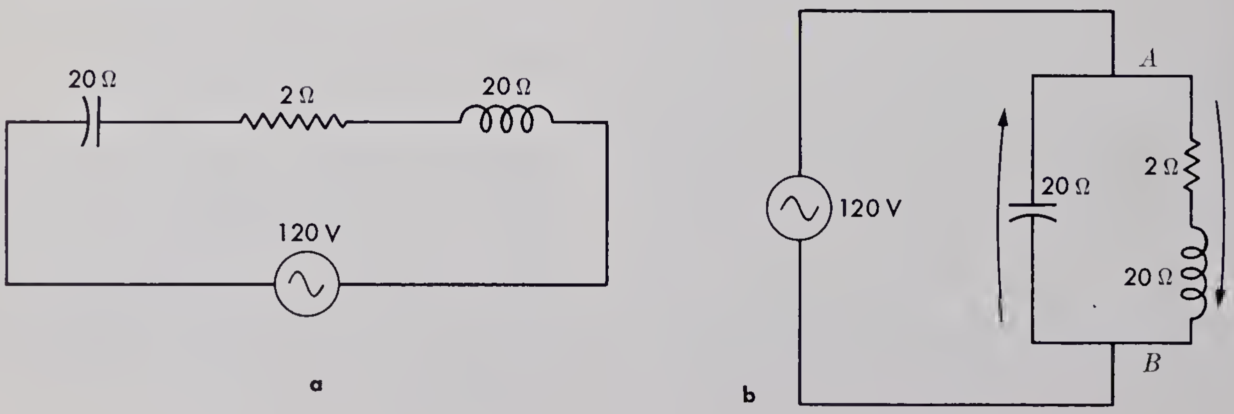
$$= \frac{1}{2\pi \times 8.5 \times 10^{-3}}$$

$$= \frac{10^3}{53.4}$$

$$= 19\ \text{cps}^*, \quad \text{Answer}$$

In a resonant circuit, the oscillations can be made to continue if additional energy is supplied. Two ways of doing this are shown in Fig. 13–12. If the frequency of the emf supplied by the generator is the same as the resonant frequency, then a large current will exist in the inductor and capacitor. If the frequency supplied is not equal to the resonant frequency, the capacitor and the inductor do not operate well together, and do not resonate. Resonant circuits are very common in radio and television transmitters and receivers, where it is important to control a frequency or to tune in to a particular frequency.

Figure 13–12 **a.** In this series arrangement of components, the inductive reactance X_L and the capacitive reactance X_C are equal but opposite. Only the resistance R remains uncancelled. Accordingly, the current in all components is surprisingly high. Since all components are in series, the current is identical in each. **b.** In this parallel resonant circuit the current in the inductive branch is almost exactly 180° out of phase with that in the capacitive branch. If it were not for the unavoidable resistance in the inductor, they would be exactly opposite. In view of this, although the circulating current within the resonant loop may be very high, the net current in the external circuit may be very small. The potential difference between A and B is high.



a

b

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[*] Units have not been written into the solution because it is not obvious that you get cps for the answer. However, if you go back to the definitions of the henry and the farad, you can prove that the denominator of the equation is seconds. Try it.

Self Check

1. How can a capacitor act as part of an ac circuit when no electrons flow through it?
2. How can the opposition of a capacitor to alternating current be computed?
3. Will more current flow in a capacitor circuit when the frequency is high or low?
4. When ac is used with a capacitor, which reaches a maximum first — the current to the plates or the potential difference across the plates?
5. If the current in a circuit leads the potential difference by one sixth of a complete cycle, what is the phase difference?
6. Why is an emf induced in a coil in an ac circuit?
7. What is the effect of the emf induced in an inductor?
8. Define the unit of self-inductance.
9. How is the reactance of an inductor computed?
10. How is the current through a coil affected by an increase in frequency?
11. When ac is used with an inductor, which reaches a maximum first, the current or the potential difference?
12. Under what conditions will there be resonance in an ac circuit?

Problems

Ⓐ 1. What is the reactance of a 2.00-μF capacitor when used in a 400-cycle circuit?

2. What size capacitor must be placed across a 120-V, 60-cycle line so that 0.50 A of current will exist in the leads to and from the capacitor?

3. At what frequency will a 30-μF capacitor permit a maximum instantaneous current of 40 milliamperes when a potential difference of 1.2 V rms is applied?

4. A magnetic flux of 0.015 Wb links through a 40-turn coil. When the current and the field dwindle to nothing, an average emf of 75 V is induced. How long did it take for the field to decrease to zero?

5. The current in an inductor is reduced from 0.20 A to 0 in an interval of 10 millisec. During this action, an average induced emf of 1.5 V is observed. What is the inductance of the coil?

6. What is the reactance of a 6.5-H inductor when used in a 400-cycle circuit?

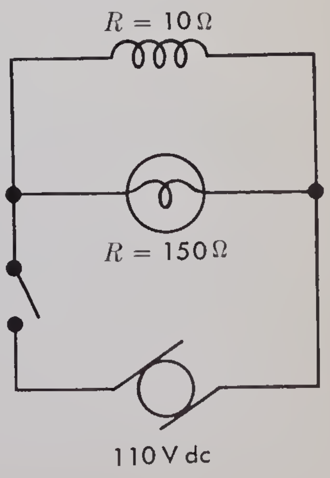
7. What size should an inductor across a 120-V, 60-cycle line be so that 0.50 A of current will exist in the inductor?

8. What is the resonant frequency of an inductor of 0.015 H connected in series with a capacitor of 0.0020 μF?

9. What is the inductance of a coil whose reactance at 400 cps is equal in magnitude to that of a 0.20-μF capacitor? At what frequency would these two reactors constitute a resonant circuit?

Discussion Questions

1. Why does an iron core increase the inductance of a coil of wire?
2. A circuit consists of a capacitor across which there is an alternating emf. If the emf is kept constant at 50 V, but its frequency increases from 60 cps to 100 cps, what happens to the current?
3. If the capacitance of the circuit of Question 2 is increased, what happens to the current?
4. A circuit consists of a coil across which there is an alternating emf. If the emf is kept constant at 50 V, but its frequency increases from 60 cps to 100 cps, what happens to the current?
5. If the inductance of the circuit of Question 4 is increased, what happens to the current?
6. If a circuit is set up as shown and then the switch is closed, the light will glow brightly for a moment and then dim. Explain.
7. What should happen in the circuit of Question 6 when the switch is opened?



Transformers

13–17 A transformer has two separate windings. Did you know that you can cause a meter to deflect when it is connected only to a coil of wire, with nothing else in the circuit? You can do it with an arrangement similar to the one in Fig. 13–13.

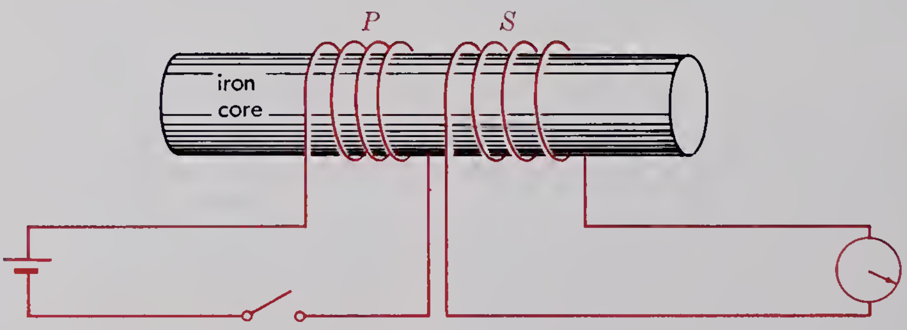
You already know that when current increases or decreases in a coil, the magnetic flux through the coil changes and produces a self-induced emf in the turns of the coil. In Fig. 13–13, winding *P* provides precisely this situation of self-induction. But because of the iron core, almost all of the flux through winding *P* also goes through winding S. Since the coils are identical, an emf is induced in S that is equal to the self-induced emf in *P*. As the switch is closed, the flux increases, and the meter deflects in one direction. When the switch is opened, the flux decreases, and an emf is induced in the opposite direction. Notice that as long as the current in *P* is constant (or 0, which is a special case of being constant), there is no flux change and hence no induced emf in S. However, when the circuit is made or broken, energy is actually transferred from one winding to the other. This is the basic principle of an electric **transformer**.

Although two coils are sometimes operated in this fashion, more commonly alternating current is used to provide energy for one of the windings, called the **primary winding**. The flux in the iron core continually changes sinusoidally, inducing a sinusoidal emf in the **secondary winding**.

The two coils in Fig. 13–14 are identical. If you were to measure the input and output potential difference in these two windings, you would find them essentially equal. Indeed, if no energy were lost as heat or sound, the input and output potential differences would be exactly the same. Each winding has 600 turns. This amounts to 5 turns for each volt (or $\frac{1}{5}$ of a volt per turn), a fairly typical figure for small transformers. Thus the potential difference across the primary winding produces a potential difference across the secondary winding on a turn-for-turn basis.

13–18 A transformer may be used to change potential difference. Transformers with unlike primary and secondary windings can increase or decrease the potential difference. For example, the transformer of Fig. 13–15 has 600 turns in the primary and

Figure 13–13 When you close the switch in the circuit at the left, the meter in the circuit at the righ deflects in one direction. When you open the switch, the deflection of the meter is in the opposite direction.



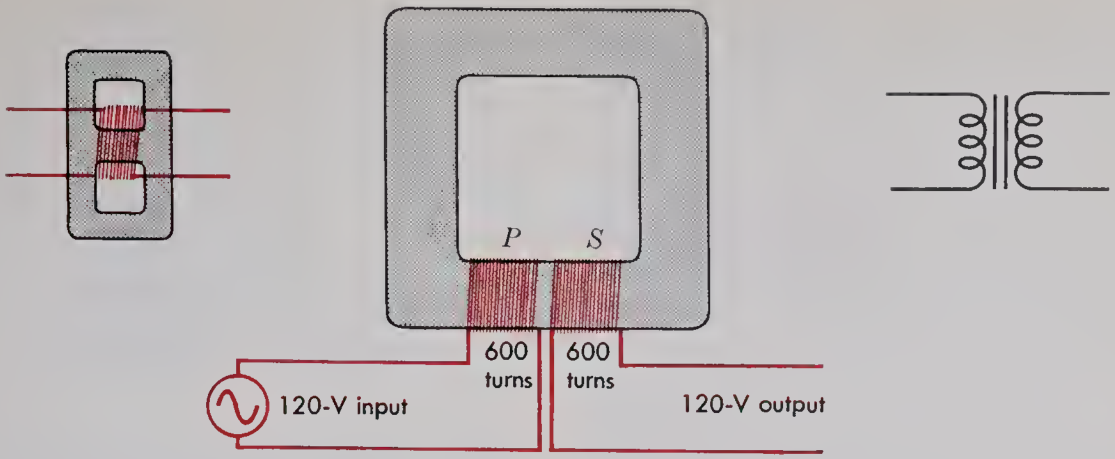


Figure 13–14 In this idealized transformer, identical coils constitute the primary and secondary windings. Accordingly, if losses are ignored, the input potential difference is the same as the output potential difference. In practice, transformer windings are often wound around the center leg of a core like that at left above. The symbol for a transformer, regardless of shape or size, is at right above.

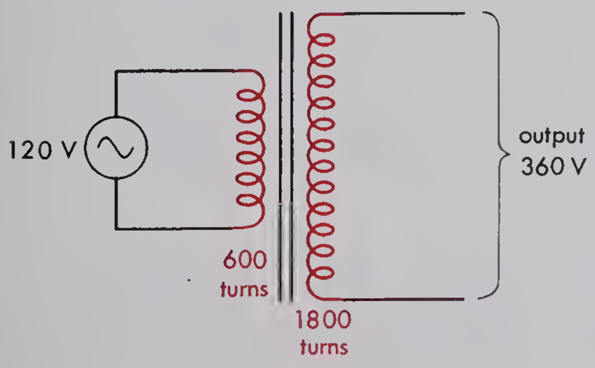
1800 in the secondary. Current fluctuations in the primary still induce $\frac{1}{5}$ of a volt in each turn; as a result, the secondary output is increased to 360 volts. This is a **step-up transformer.**

In an ideal transformer the potential differences in the primary and secondary windings are proportional to the number of turns in each. Stated mathematically:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

where V_p and V_s are potential differences of primary and secondary, respectively, and N_p and N_s are the number of turns of the primary and secondary, respectively.

Figure 13–15 This schematic diagram represents a transformer with a turns ratio of 1 : 3.



The ratio of the number of turns in the primary to the number of turns in the secondary (N_p/N_s) is called the **turns ratio** of a transformer. The turns ratio is greater than unity in a **step-down** transformer; it is less than unity in a step-up transformer.

13–19 Transformers illustrate the principle of conservation of energy. Is the ability of transformers to change the potential of a source of electricity a violation of the principle of conservation of energy? Not at all. Potential difference is not a measure of energy, but of *energy per unit charge.* The total energy in either winding is the product of the potential difference (energy per unit charge) and the number of charges (current × time). Then, according to the law of conservation of energy,

$$\left[\begin{array}{c}\text{potential difference} \times \text{current} \times \text{time} \\ \text{in primary winding}\end{array}\right]$$

$$= \left[\begin{array}{c}\text{potential difference} \times \text{current} \times \text{time} \\ \text{in secondary winding}\end{array}\right]$$

Since the time is the same for each winding:

$$V_p I_p = V_s I_s$$

where V_p and I_p are potential difference and current in the primary winding, respectively, and V_s and I_s are potential difference and current in the secondary winding, respectively. Thus, except for the inevitable heat loss in a transformer, power input and power output are the same. In modern large transformers, this loss can be reduced below 1 percent of the total power handled.

13–20 Inductors can be made to operate with dc. Sometimes it is necessary to have the benefit of a step-up of potential difference when the only source of electric energy is dc. An excellent example is the automobile engine, where the 6- or 12-volt storage battery must somehow provide a high potential — perhaps 15 to 40 thousand volts — for proper spark plug operation. The solution to this problem lies back in Fig. 13–13, where a primitive transformer was operated bv opening and closing a switch in the primary circuit.

Remember, such a switch-operated transformer delivers energy only when the switch is being closed or opened. Therefore, the switch should be operated very rapidly. An easy way to accomplish this is to interrupt the primary circuit with a vibrating switch or a rotary switch. A step-up transformer operated in this way with interrupted direct current in its primary winding is an **induction coil**.

In Fig. 13–16, the primary and secondary windings are connected together forming a single winding. However, since the device is a step-up arrangement, potential difference is lower and current is higher in the primary part of the winding than in the secondary part. Accordingly, the primary winding is made of heavier wire. The primary current is interrupted by the contact points of a doorbell-like buzzer. The output in such a "spark coil" may be many thousands of volts.

In an automobile ignition system the "make" and "break" of the primary is accomplished by a rotary switch. The timing is arranged so that a "break" occurs each time a spark is needed in any cylinder.

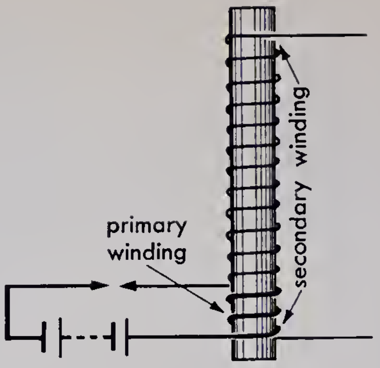


Figure 13–16 A simple induction coil has a single winding, although the part used for the primary is often heavier wire than the remainder. Current in the primary is interrupted by buzzer-type contacts or a high-speed rotary switch. The output potential difference may be many thousands of volts.

A Tesla coil, a special kind of step-up transformer, can be made to deliver a million volts or more.

13–21 Long-distance transmission of electric energy might be very expensive. Commercial electric power systems transmit power over a distance. In many cities, this seldom exceeds a few miles. However, where electric energy is converted from water power in remote areas, the transmission lines may extend hundreds of miles.

Imagine the engineering problem of conveying large quantities of electric power over even moderate distances. Assume that 50.0 kilowatts of power (enough for only a small city block) are transmitted over a distance of 10 mi and that the energy is delivered at the usual potential difference of 120 volts. Now apply the power formula to find the current:

$$P = VI$$
$$I = P/V = 5.00 \times 10^4 \text{ W}/120 \text{ V}$$
$$= 417 \text{ A}$$

To cut down the power loss in the lines themselves, suppose that very large wire is used, and that the total resistance of two 10-mi conductors is only 5Ω. Another version of the power formula now gives the power lost as heat in the lines:

$$P = I^2R = (417\ \text{A})^2 \times 5.00\Omega$$
$$= 8.70 \times 10^5\ \text{W} = 870\ \text{kW}$$

And what of the fall of potential in the line? This can be determined with Ohm's law:

$$V = IR = 417\ \text{A} \times 5.00\Omega = 2080\ \text{V}$$

To deliver 50 kilowatts of electric power, the generating station would have to provide not only that power, but an additional 870 kilowatts for line losses, and the potential difference at the generator terminals would be 120 volts plus the line drop, or a total of 2200 volts. Very wasteful, indeed!

Evidently the principal factor in the losses is the high current. This suggests the use of a transformer to step the current down (and the potential difference up). Thus, if a 1:1000 step-up transformer is used, the 50 kilowatts of power will be sent at a potential difference of 120,000 volts, but at a current of 0.417 amperes. The line loss under these conditions is $I^2R = (0.417\ \text{amperes})^2 \times 5\Omega = 0.87$ watt, which is insignificant compared to the total power delivered. Furthermore, the size of the wire used can be greatly reduced without unduly increasing the line loss. This alone is a great saving in installation cost. Of course, a step-down transformer must be used at the load end, since a potential difference much greater than the customary 120 volts would be dangerous in the home or office.

This cost-saving feature of high-voltage transmission lines is one of the outstanding advantages of ac over dc. Modern high-potential transmission lines operate at potentials of from a few thousand volts to as high as half a million volts.

Self Check

1. Why is an emf induced in the secondary of a transformer when current changes in the primary?
2. A transformer for a neon-type advertising sign must deliver 9000 volts to the lighting unit. Ignoring losses, what should be the turns ratio of a transformer to supply this when operated from a 120-volt primary?
3. If the current to the primary of the transformer of Question 2 is 15 amperes, what is the current in the lighting unit?
4. Is the transformer of Question 2 a step-up or step-down transformer?
5. What factor prevents the power delivered by the secondary of a transformer from being equal to the power input of the primary?
6. How can an induction coil operate on direct current?
7. Why would long-distance transmission of electric power, if done at low potentials, incur heavy losses?
8. How does the use of alternating current help solve problems of transmitting electric energy over long distances?

Problems

A 1. What should be the turns ratio of a transformer used to operate a 10-V doorbell from a 120-V line?

2. If the transformer of Problem 1 is designed to have 4 turns per volt in each winding, how many turns will there be in the secondary?

3. In Problem 1, what is the primary current if the bell draws 2.5 A and the efficiency of the transformer is 80 percent?

4. A small welding transformer draws 8.0 A from a 240-V line, and delivers a current of 90 A at a potential difference of 14 V. What is the efficiency of the transformer?

B 5. A transformer is designed to be fed by a 600-V ac generator to feed a 110,000-V transmission line. The designer decides to use 2,700 turns in the primary winding. If all the losses combine to reduce the secondary output potential by 4.0 percent, how many turns should the secondary winding possess?

Discussion Questions

1. If the primary and secondary of a transformer are wound on separate cores and are placed several inches apart from each other, will an emf be induced in the secondary when alternating current exists in the primary?
2. Why is the secondary winding of a step-up transformer frequently made of finer wire than the primary winding?

Alternating Current Motors

13–22 An induction motor resembles a transformer. Many of the electric motors used in modern Canadian homes are of a type quite different from those described in Chapter 12. Typical motors in washing machines and refrigerators, clothes dryers and shop tools, are induction motors, which operate only on alternating current.

The field windings of a typical induction motor are diagramed in Fig. 13–17. Note that at the first instant shown, the four poles are alternately N and S. One half cycle later — that is, 1/120th second later — each one has reversed. Now this magnetic field can be thought of as having rotated through 90° of a circle during the half-cycle intervals. Actually it makes no difference in which direction you assume it to rotate, but in this discussion assume that the magnetic field goes clockwise. Notice that the field core and windings themselves do not move, but the magnetic field which they produce goes through a pattern of changes much as if the core and windings were rotating.

The armature, or rotor, of the induction motor (Fig. 13–17c) consists of heavy copper (or aluminum) bars imbedded in a core of soft iron. The resemblance of this structure to a small animal cage accounts for the fact that such a motor is frequently called a **squirrel-cage motor**. There are no electrical connections to the rotor-armature.

The rotor is located within a rotating magnetic field. Therefore, the flux density within the conductors of the rotor is constantly changing. The motor is like a transformer. The field winding is the primary, and the squirrel-cage rotor, the secondary. An emf is induced in the copper bars of the rotor, and since the bars constitute a complete circuit, an induced current results. And now, according to Lenz's law, the induced currents set up magnetic fields which oppose the cause of those currents.

What is the cause of the currents? It is the relative motion between the rotating magnetic field and the stationary armature, or rotor. This relative motion may be opposed by having the rotating magnetic field stop or by having the rotor move. The rotor, of course, moves. If the rotor moves at the same speed as the rotating magnetic field, then the two are not in relative motion and there is no induced current. Thus under normal loads, the rotor of an induction motor always rotates at a speed slightly

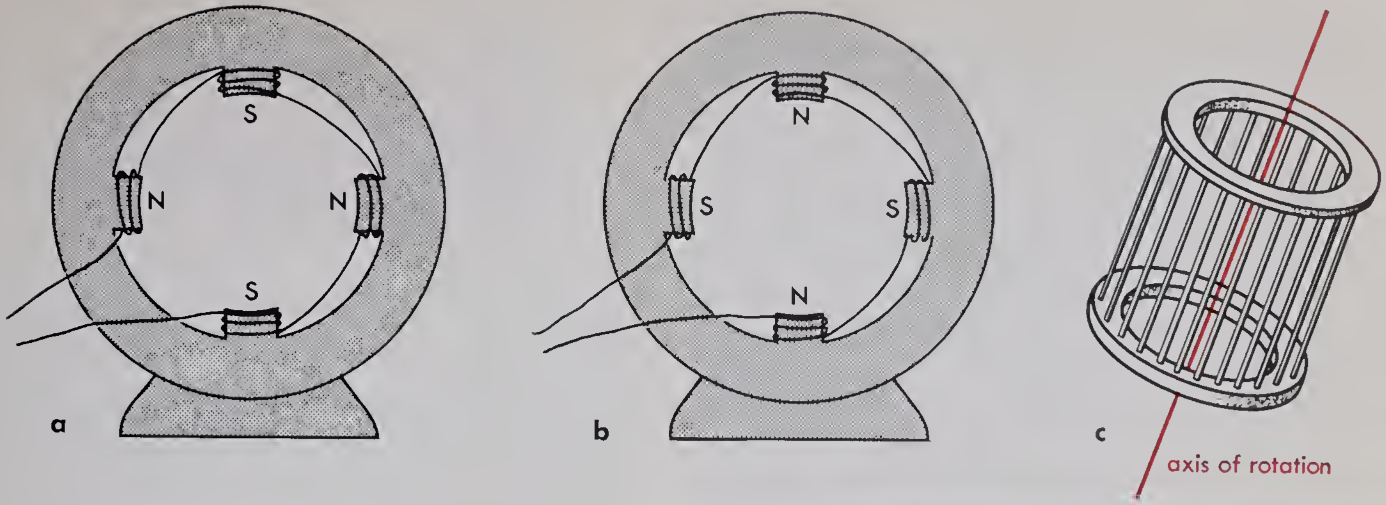
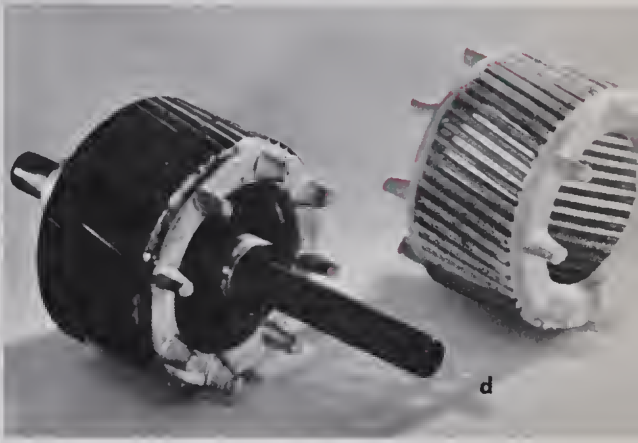


Figure 13–17 In **a** and **b** the four poles of the field of an induction motor are shown at two instants one half of a cycle apart. Note that each pole is wound in an opposite direction from the adjoining poles. Therefore, adjacent poles have opposite polarity. **c.** This is a diagram of a squirrel-cage armature. Its conductors are usually made of heavy copper imbedded in highly permeable iron. Note that there is no commutator in this kind of motor. **d.** The rotor of an induction motor. On the left is the rotor and the shaft to which it is connected. At the right is the aluminum "squirrel-cage" part of the rotor.



less than that of the rotating magnetic field, which supplies the energy for motion. The rotating field in the motor of Fig. 13–17 moves at 1800 rpm. Hence, a typical motor of this kind is usually rated at 1700 to 1750 rpm.

The rotating magnetic field of Fig. 13–17 might be considered as either clockwise or counterclockwise. As a matter of fact, the rotor in such fields also can move in either direction, depending on which way it is started. The rotor cannot start from a resting position without help. Consequently, induction motors have a special circuit which starts them in the desired direction. Once started, the motor quickly accelerates until it is operating at its rated speed.

It is also possible to design ac motors which operate at a precisely constant speed, regardless of mechanical load. These are called **synchronous motors**. In large sizes they are valuable in complex and exacting industrial situations. Electric clocks use very small synchronous motors.

Do It Now

Listen carefully as the motor of your refrigerator, washing machine, or power saw starts. Do you hear a click a fraction of a second after the motor begins to rotate? This is an automatic switch which opens the circuit for the starting device of the motor; once the motor is moving, it no longer needs the starting device. When the motor is turned off and slows down, the automatic switch closes (and clicks) again, so it will be ready to operate when the motor is started once more.

13–23 Lenz's law is an important generalization. The explanation of the operation of a squirrel-cage motor provides an excellent example of the value of a generalization, or concept — in this case, Lenz's law. You could, of course, have learned the operation of this motor without it. You would have had to analyze the direction of induced emf and the resulting current, and then determine the polarity of the magnetic field which the induced currents produced. This done, you would have had to see how the rotor's magnetic field interacts with the stator's magnetic field. All this is possible, of course, but it would make an extremely involved explanation. The principles of the operation are themselves simple, but are complicated by the changing magnetic field of the stator and by the very unusual circuit formed by the copper bars and the rings of the rotor.

Lenz's law, however, covers many situations, including the squirrel-cage motor. Knowing it, you need only recall that currents induced in the rotor set up a magnetic field which opposes the cause of those currents. Then you re-identify the original relative motion, and the operation of the motor is explained. This shows the value of such a powerful concept as Lenz's law: it greatly simplifies the explanation of otherwise difficult situations.

13–24 Ac motors have many advantages over dc motors. The induction motor operates only with ac circuits. This type of motor has certain advantages and disadvantages when compared with dc motors.

Disadvantages

1. Induction motors must be provided with special starters.
2. Induction motors do not operate well at speeds much lower than their rated speeds. As a result, they have low starting torque, and continued low-speed operation may damage them. They are not variable-speed devices.
3. Induction motors are larger and heavier than brush and commutator motors of the same horsepower.

Advantages

Because induction-type motors have neither commutator plates nor brushes:

1. They are cheaper to build — no commutators, no brushes, no armature windings.
2. They operate more quietly.
3. They present a minimum upkeep problem — no brushes to replace, no commutator to be cleaned. With lifelong lubrication systems, some induction motors have operated normally for many years without attention.
4. Having no brushes, induction type motors create no sparks. This is a particularly valuable asset in mines, around gasoline fumes, or in other places where a spark might cause an explosion.

Self Check

1. How can current exist in the armature of an induction motor where there are no electric connections to the conductors built into the armature?
2. Why does the armature of an induction motor normally rotate slightly more slowly than the magnetic field of the stationary coils?
3. What determines the direction in which a squirrel-cage motor rotates?
4. What features of an induction motor make for reduced maintenance costs as compared with a dc motor of similar size?

Chapter Summary

In an alternating current circuit, both potential difference and current vary sinusoidally. The most common frequency for this variation is 60 cps. The ac ampere is defined as the current which produces the same heating effect as 1 dc ampere. Ac potential difference and current are measured in effective or rms values. The effective value of a sinusoidal variation is 0.707 times the maximum value which it reaches. Permanent-magnet, moving-coil meter movements can be adapted to ac measurements by using rectifiers. In addition, special ac meter movements have been designed for ac measurements. In spite of the constant variations of values of potential difference and current, Ohm's law applies to alternating current circuits providing they are purely resistive. Commercial alternating current is produced by ac generators. These usually have rotating fields and stationary armatures.

Capacitors in ac circuits are subject to constant changes in potential difference across their plates; hence electrons are always flowing into or out of the capacitors. The opposition or capacitive reactance which capacitors present in ac circuits is inversely proportional to the capacitance and to the frequency. When an ac potential difference exists across the terminals of a capacitor, the alternating current leads the potential difference by a phase difference of 90°. When alternating current exists in a loop of wire, there is constantly changing magnetic flux within that loop which induces a corresponding emf, whose polarity opposes the current change which caused it. As a result, inductors oppose changes in current in them, and they oppose alternating current, since it is constantly changing. This property of an inductor is its inductance. A coil or inductor has an inductance of 1 henry (H) if a current change of 1 ampere/sec produces an emf of 1 volt. The opposition which an inductor presents to alternating current is its inductive reactance. This varies directly with the inductance of the inductor and with the frequency of the current. When an ac potential difference exists across the terminals of an inductor, the resulting alternating current lags the potential difference by a phase difference of 90°. Circuits containing both capacitance and inductance oscillate at a resonant frequency at which capacitive reactance and inductive reactance are equal.

In a simple transformer, two coils are placed close to each other around a core of high relative permeability. When varying current in the primary winding produces flux changes and hence an emf in that coil, it does so also in the secondary winding. Transformers can be designed either to step up or step down the potential difference. When potential difference is increased from primary to secondary, current is decreased by the same factor, in accordance with the law of conservation of energy. An induction coil uses interrupted direct current in its primary winding, which is often electrically connected to the secondary winding. Transformers permit the transmission of electric energy over long distances at very high potentials and very low currents, thus reducing the heating-effect losses which heavy current would otherwise produce.

In an induction motor, currents are induced in the squirrel-cage-like conductors of the rotor by transformer action from the field windings, and produce forces which cause the rotor to turn. Induction motors have certain advantages over brush-type motors, including economy of construction and maintenance.

Vocabulary

instantaneous value (*p. 304*)
alternating current (*p. 304*)
maximum value (*p. 304*)
phase angle (*p. 304*)
cycle (*p. 304*)
frequency (*p. 304*)
ac ampere (*p. 304*)
effective value (*p. 304–305*)
rms value (*p. 305*)
resistive circuit (*p. 306*)
rectifier (*p. 306*)
capacitive reactance (*p. 309*)
lead (*p. 310*)
phase difference (*p. 310*)
self-induction (*p. 310*)
inductance (*p. 311*)

inductor (*p. 311*)
henry (*p. 311*)
choke coil (*p. 312*)
inductive reactance (*p. 312*)
lag (*p. 313*)
impedance (*p. 313*)
oscillating circuit (*p. 315*)
resonant circuit (*p. 315*)
resonant frequency (*p. 315*)
transformer (*p. 318*)
primary, secondary winding (*p. 318*)
step-up transformer (*p. 319*)
turns ratio (*p. 319*)
step-down transformer (*p. 319*)
induction coil (*p. 320*)
induction motor (*p. 322*)
squirrel-cage motor (*p. 322*)
synchronous motor (*p. 323*)

Problems

Ⓐ **1.** At a given instant, the potential difference in a 60-cycle ac circuit is 0. If the peak value is 10 V, what is the potential difference 1 cycle later; 1 sec later; ¼ cycle later?

2. An ammeter shows that a steam iron draws 6.0 A. What is the maximum instantaneous current in the appliance?

3. A technician happens to have an ammeter and a voltmeter both of which, contrary to practice, measure maximum values rather than effective values. According to these instruments, a given industrial heater draws 10 A at 100 V. What is the power consumed by the heater?

4. A voltmeter shows that the potential difference across a 6.0-μF capacitor is 30 V at a sinusoidal frequency of 1200 cps. What current exists in this part of the circuit?

5. An ammeter shows that a current of 0.75 A at 60 cps exists in a circuit which contains a 25-μF capacitor. What is the maximum potential difference which exists across the capacitor terminals?

6. A circular coil of 60 turns and 12-cm diameter lies perpendicularly across a magnetic field of 0.015 T. What is the average emf induced in the coil if the field falls to half its flux density in an interval of 1/100 sec?

7. What is the average emf induced in a 2.5-H inductor when the current in it rises from 1.8 A to 4.3 A in 0.30 sec?

8. A good choke coil with large-size wire may be considered for many purposes as a pure inductor (i. e., the resistance of the wire is ignored). It is desired to design such a coil so that it will draw 3.5 A when operated on a 120-V, 60-cycle line. What should its inductance be?

9. Radio receivers use resonant circuits to select the frequencies of desired broadcast signals. The common capacitor to use in such a circuit is one whose capacitance is 365 pF. What inductance should be used with this to make a circuit resonant at the lower end of the broadcast radio band, which is 540 kc/sec?

10. A transformer is designed to operate on a 120-V line and supply 8 V to operate a buzzer. The primary winding has 600 turns. How many turns are in the secondary winding?

11. A welding transformer operates from a 240-V primary, and delivers 80 A of current at 15 V to the welding unit. If the efficiency of the transformer is 75 percent, what is the current in the primary?

Ⓑ **12.** The gas in a low-pressure, gas-discharge lamp (neon-type) is known to ionize and give off light when the potential difference between plates is 70 V, and to continue to do so until it falls to 20 V. During what fraction of the time does the lamp glow when operated from an ac power supply whose maximum potential difference is 100 V?

Discussion Questions

1. In 60-cycle alternating current, there are 120 instants each second when the potential difference is 0. In a purely resistive circuit, what is the instantaneous value of the current at these intervals?
2. Some older commercial power systems use 25-cycle current. Can you imagine any disadvantage in using this current for electric lighting?
3. A circuit contains resistance and inductance. For a certain value of frequency, the phase difference is 80° Describe what happens to the phase difference if the frequency is increased?

4. A circuit contains resistance and capacitance. For a certain value of frequency, the phase difference is 80°. Describe what happens to the phase difference if the frequency is increased?
5. As you tune your radio to stations of higher and higher frequency, are you increasing or decreasing the capacitance of the tuning capacitor? Examine the tuning capacitor. Why does turning the knob change the capacitance?
6. If high potential differences and low currents make for more economical transmission of electric power, why are not household electric lines operated in this manner?

Work on Your Own

1. If your school has ac meters, set up ac circuits containing resistance, inductance, and capacitance. Measure the potential difference across various parts of the circuit. You will find that Kirchhoff's laws do not seem to apply, and you may wish to learn more about how they must be modified in ac circuits. Be careful about the capacitors you use. Some are designed to be used only with direct current and will overheat or even explode with alternating current.
2. Find out more about ac meters.
3. Take some capacitors apart to see how they are made. How is the problem of large area solved without making the capacitor too bulky?
4. Connect the secondary of a doorbell transformer to a galvanometer, and the primary to a dry cell. Observe the behavior of the meter when you open and close the primary circuit switch.
5. Make your own transformer with two separate coils. Investigate the effect when the coils are on the same core, separate cores, and at various distances.

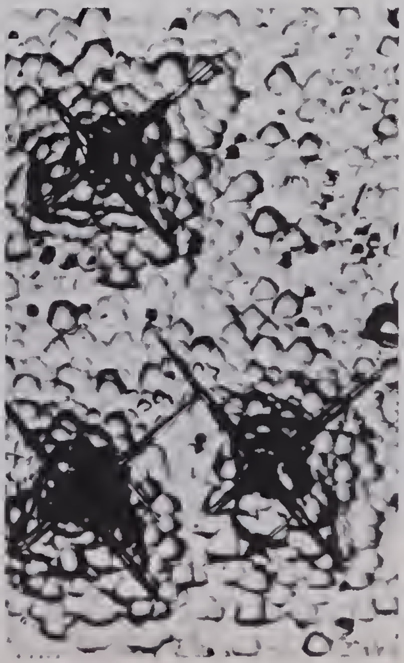
UNIT FOUR

Electronics

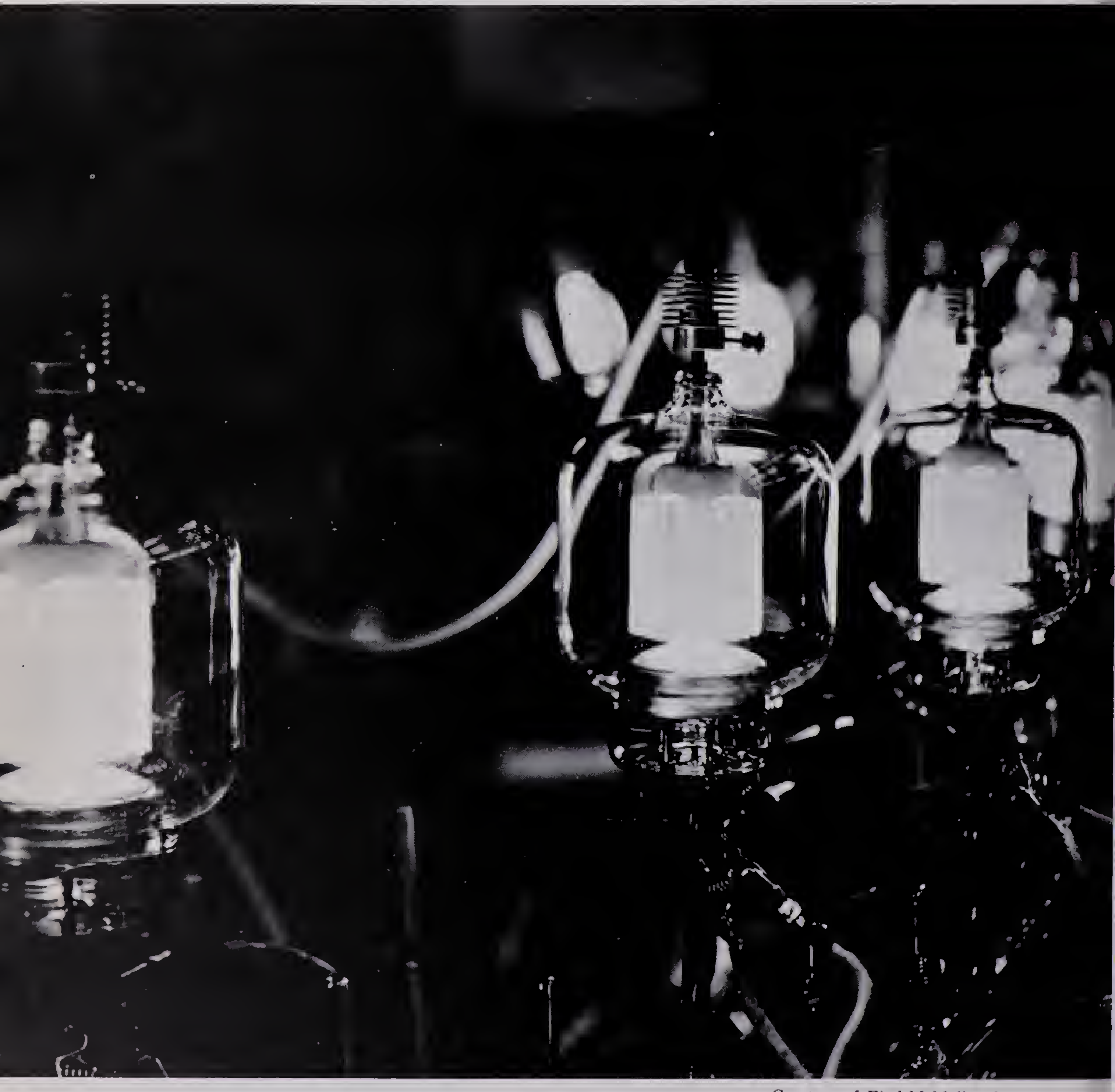
Courtesy of General Electric Research Laborato

Irving Langmuir, J. J. Thomson, and William D. Coolidge inspect an early vacuum tube. Between 1895 and 1915 these men made discoveries that are important in modern electronics.

By now you have learned of the electrical nature of matter and have studied some of the fundamental concepts of electric energy and electric circuits. With this background you are ready to explore one of the most useful branches of physics and engineering — electronics. In this unit you will learn how electron flow is controlled for useful purposes by means of certain specialized circuits, including vacuum tubes. In particular, you will learn how such circuits convert alternating current to direct current and how they amplify weak signals for a wide variety of uses in electronic communication. Man's understanding and control of electron flow has produced many highly useful technological devices. Of more fundamental importance, man has gained valuable evidence concerning the nature of the universe in which he lives. Accordingly, the last chapter of this unit provides a survey of some of the more recent phases of man's exploration of matter and energy.



CHAPTER 14



Courtesy of Eitel-McMullough, Inc.

Tetrode vacuum tubes have four electrodes. They were an early improvement over the triode because they operated much better with the frequencies of radio waves than did triodes.

Electron Tubes and Electronic Circuits

A good look at the circuit diagram of a TV set or hi-fi system can be a terrifying experience. There are resistors and capacitors, inductors and transformers, wires and switches. There may be strange symbols representing antennas, microphones, or speakers. Furthermore there are vacuum tubes, devices about which you know very little.

The circuits are complicated. Many wires come together in some places; there are many complete paths or circuit loops. But Kirchhoff's rules apply here as well as in simple circuits. So do Ohm's law and the power formula. You already know a great deal about electronics circuits.

Most important of all, you know about electrons and why they flow in circuits, how they behave in resistors, inductors, and capacitors. When you have learned how electrons behave in a vacuum, you will see that electronic circuits, like other circuits, can be understood in terms of physics fundamentals.

In this chapter you will learn about electric currents in a gas and in vacuum, and how such electronic currents behave in simple electron tubes.

Electric Current in a Gas

14–1 Gas-discharge tubes are common devices. Have you ever wondered how neon-type advertising signs or fluorescent lamps fit in with what you know about electric current in solids?

If you examine a neon-type sign closely, it appears to be empty glass tubing. Sometimes the tubing is colored or appears to have some sort of pastel paint inside. If you break open a discarded fluorescent lamp, you find that a powdery chemical is on the inside surface of the tubes. **(Be extremely careful with these chemicals because they are very poisonous, particularly if they get into tiny cuts in the skin!)** The electrical connections seem to be little more than short bare wires sealed into the ends of the tubing. There is a gas present inside the tube at very low pressure, but of course you cannot see this.

Advertising signs use gas tubes to produce any desired color, yet for the most part, the glass tubing itself is colorless. These sources of light operate at low temperatures. Even after glowing for several hours, neon-type signs and fluorescent lamps are only slightly warm. Here then is something which bears further investigation. It appears that under certain conditions, *gases* can conduct current, and that one result of this current is the emission of useful light.

Do It Now

Next time you go past a store window where there is a neon-type sign, stop and look at it very closely. Examine the electric connections at the ends of the tube. Can you find any way for current to get from one end of the tube to the other?

14–2 Gas-discharge tubes operate at very low pressure. A very simple kind of gas-discharge tube is diagramed in Fig. 14–1. A straight glass tube a foot or more in length is connected to a vacuum pump. Electric connections inside the tube are provided by metal plates called **electrodes** whose supports are sealed into the glass ends. The electrodes are connected to an induction coil providing a potential difference of several thousand volts.

When the gas in the tube is at atmospheric pressure, no discharge occurs. As the pressure is reduced, a few lightning-like sparks leap from one electrode to the other (see Fig. 14–2). When the pressure is at about 10^{-2} atmosphere, a violet-colored light extends the length of the tube (Fig. 14–2b). At about 10^{-3} atmosphere the negative electrode appears to be coated with a soft velvety light, while the remainder of the tube is filled with alternate regions of light and darkness (Fig. 14–2c). Finally if the pressure is reduced to approximately 10^{-6} atmosphere, little or none of the gas glow remains. However, much of the glass wall surrounding the gas discharge glows with a distinct greenish or bluish light.

Figure 14–1 This is a diagram of a simple gas-discharge tube. The induction coil supplies the high potential difference required.

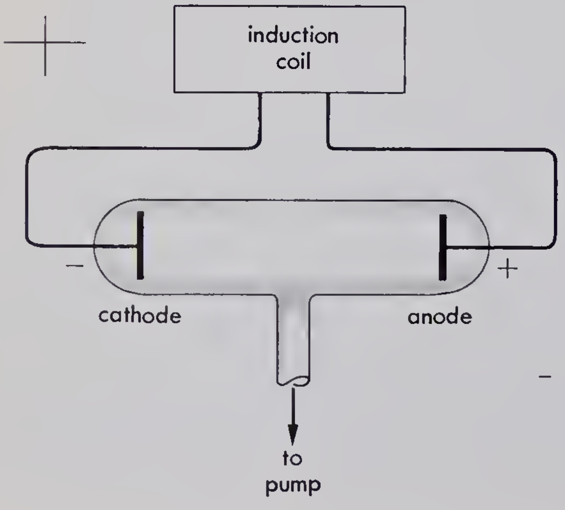
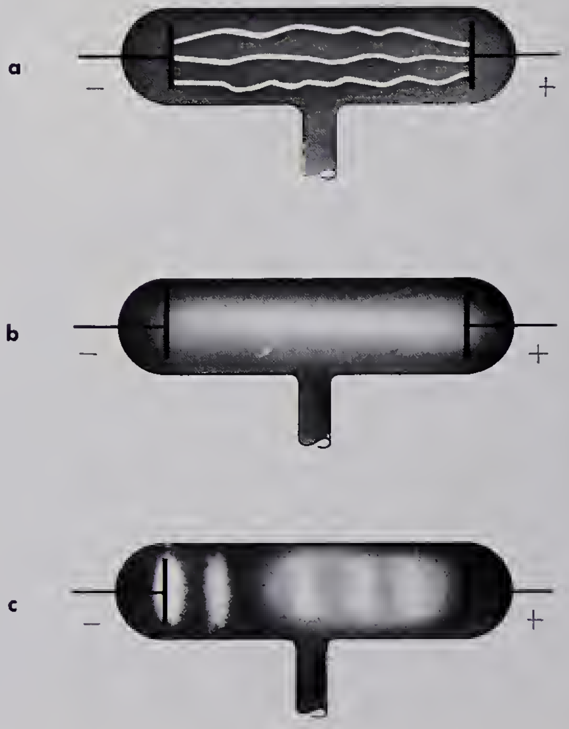


Figure 14–2 These diagrams show the progression of glow in a simple gas-discharge tube as the pressure is reduced.



The development of the gas-discharge tube just after the middle of the nineteenth century is closely linked with the names of two scientists, Heinrich Geissler of Germany and William Crookes of England. Geissler developed the vacuum pump capable of producing very low gas pressures. And he was first to operate a low-pressure discharge tube. Crookes made exhaustive studies of this kind of electric current and laid the foundation for present knowledge of current in gases. It is not surprising, then, that low-pressure gas-discharge tubes are commonly referred to as Geissler tubes or Crookes tubes.

14–3 Moving ions constitute the current. Experiments have shown that when the pressure of a gas is low enough, a strong electric field splits the gas atoms or molecules into ions. If the gas is a simple element, such as oxygen, nitrogen, or chlorine, the molecules lose one or more electrons; what remain are positive ions. The "lost" electrons, of course, are negatively charged and may be considered negative ions. Due to the electric field, the positive ions move toward the negative electrode, and the negative ions toward the positive electrode. Thus, the current in the gas-discharge tube consists of the flow of negative and positive ions in opposite directions.

Once they are in rapid motion, these ions strike other atoms and molecules and ionize them. Electrons have very high speeds and are particularly effective in ionizing other atoms by knocking away some of the outer electrons. Sometimes an electron strikes an orbiting electron and does not give it quite enough energy to escape the attraction of the positive nucleus. Instead it moves the struck electron out to a larger orbit. In the larger orbit an electron has more energy because work has been done on it to move it farther from the nucleus. Somewhat later, when these shifted electrons return to their normal orbits, they radiate this energy in the form of visible light or invisible radiation. The colors of the visible light produced depend on the gas in the tube. Thus, oxygen produces a blue-violet light; carbon dioxide, pale blue; neon, bright red; and mercury vapor, intense blue-green.

When the gas pressure within a gas-discharge tube is low enough, the electric field gives the ions a very great velocity, and they move many centimeters before striking another particle. When these speeding electrons strike the surrounding glass, they produce a fluorescent effect visible as a greenish or bluish glow of the minerals in the glass itself.

14–4 Neon-type advertising signs are gas-discharge tubes. Modern tubular advertising signs are a direct application of low-pressure gas discharge. After the design has been made, the sign maker divides the letters or numbers of lines which he must make into sections a few feet long. He then bends glass tubing into the desired shape and seals electrodes into the ends. Next the tubing is connected to a vacuum pump and practically all air is withdrawn from the tube. Finally, gas to produce the desired color is admitted to the tube at the proper pressure. When sealed it is ready for operation.

The energy for operation is supplied by a transformer which provides several thousand volts across its secondary winding. The primary winding is connected to a supply of 120 volts ac. Under these conditions, each electrode is positive part of the time and negative part of the time. In this case, it makes no difference, however, since the pressure of the gas is selected to produce a continuous glow throughout the tube.

Many kinds of gases are used to produce the many colors desired. Neon produces the bright red color so often seen. Neon was, in fact, the first gas used for commercial signs. As a result, all signs of this type are commonly miscalled "neon signs." Sometimes tinted or coated glass tubing is used to achieve the special effects in today's neon advertising.

14–5 The phosphors in fluorescent lamps produce light. Household fluorescent lamps produce a discharge through mercury vapor. This provides invisible ultraviolet light, plus a very small amount of visible light. The ultraviolet radiation strikes the interior of the tube, which is coated with a mixture of chemical compounds called **phosphors**. These **fluoresce**; that is, they give off visible light when excited by ultraviolet radiation. Hence, the useful light from a fluorescent lamp is not the direct radiation from the conducting gas but secondary radiation from the chemicals on the inner surface of the glass tube. Fluorescent lamps may be made to produce any color, depending on the choice of phosphors.

The electric circuit of a typical fluorescent lamp circuit is shown in Fig. 14–3. Like most such lamps, this one is designed to operate directly from a 120-volt ac source. The two electrodes have heating filaments, which operate only while the lamp is warming up. Once the glow discharge is started, the electrodes are kept warm by the kinetic energy of ions striking them.

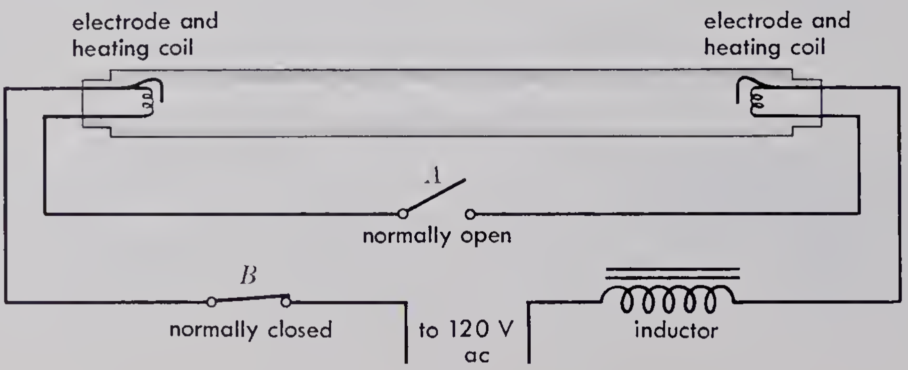
Self Check

1. How do electric charges enter and leave a gas-discharge tube?
2. Under what conditions can a gas be ionized by an electric field?
3. Why is light given off in a typical gas-discharge tube?
4. What determines the color of light given off by a gas-discharge tube?
5. Why is it that at lower pressures ions attain high speeds in a gas-discharge tube?
6. Why is ac feasible for operating neon-type advertising signs, providing the potential difference is sufficient?
7. What kind of radiation is produced by the gas discharge within a fluorescent lamp?
8. What is the major source of the visible light which fluorescent lamps produce?

Discussion Questions

1. What do you think would be the location of the soft velvety light of Fig. 14–2c if the gas-discharge tube were operated on ac rather than dc?
2. In a gas-discharge tube, orbiting electrons are moved to larger, higher-energy orbits. What is the source of energy for this change?

Figure 14–3 This fluorescent lamp is shown in a typical circuit for manual starting. To start, switch *A* is closed, thus completing the circuit through both heating coils and the inductor, all in series. When, after a few seconds, switch *A* is opened, the inductor provides the high-potential inductive "kick" to ignite the tube. Thereafter, it acts as a "ballast" to keep the current down to a safe value. To turn the lamp off, switch *B* is momentarily opened.



Electric Current in a Near-vacuum

14–6 Hot metals yield free electrons. You have seen that electric current can exist in a rarefied gas. The moving charges — positive and negative ions — are present in the low-pressure gas in the tube. They move because they are in an electric field. Surely the same sort of thing could happen in a discharge tube in which the "gas" consists of only electrons free in space. In that case, it would not be a gas-discharge tube but literally an *electron tube.* This is what the common **vacuum tube** actually is. The problem is to get a large number of free electrons in the space inside the tube. This is done by using a metal as the source of the free electrons.

You already know that metals and some other substances contain free electrons — electrons that are part of the atomic or molecular structure but are free to drift within the substance. When there is no current, the free electrons still vibrate and migrate from atom to atom, but there is no general drift in any one direction.

As might be expected, this activity of free electrons increases with temperature. If the temperature rises to about 2000°K, the free electrons become so active that they are literally hurled away from the surface of a metal and become free electrons in space. These electrons are said to be *emitted* from the metal. Since this is a *thermal* situation, and since the electrons are ions, this phenomenon is known as **thermionic emission**, which can be defined as the release of free electrons from the surface of hot conductors.

14–7 High temperatures supply the energy. Why are such high temperatures required to produce thermionic emission? Why do not electrons escape from the metal more easily? Electrostatic attraction and possibly other interatomic forces tend to hold them back.

The energy which an electron must have to escape into space is called its **work-function**. The work-function of most metals is 3 to 5 electron volts. This is greater than the energy possessed by free electrons in metals at ordinary temperatures. High temperatures are required to supply the additional energy. In fact, most metals melt before they get hot enough to emit electrons in any great quantity. Tungsten with its high melting point (3643°K) is used extensively as an emitting electrode in high-power vacuum tubes. In such applications it is operated at about 2500°K.

Many metals and some metallic oxides have lower work-functions than does tungsten, but cannot be used alone because of their low melting point, or their inability to be drawn into a wire. Fortunately, it is possible to add such materials to tungsten to improve its emission characteristics.

Do It Now

Thermionic emission has often been compared to "boiling away of electrons." Recall what you know about the energy involved in releasing molecules from a liquid to become a gas. Is there any resemblance between this and thermionic emission? What are the limitations of the analogy? In the boiling of a liquid, what corresponds to the work-function?

14–8 Many tubes have indirectly heated cathodes. In medium- and high-power vacuum tubes, a treated tungsten filament is heated by electric current and then emits electrons. Such an arrangement is called a directly heated electrode. In

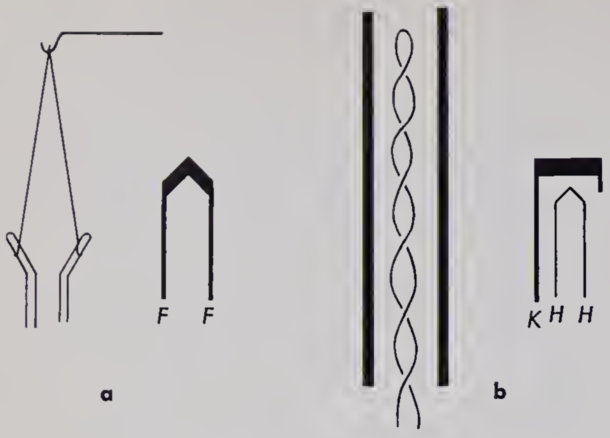


Figure 14–4 **a.** This drawing shows the structure of a directly heated cathode. The upper support keeps the filament strands taut, even when they expand on heating. Beside the drawing is the symbol used in circuit diagrams to indicate a directly heated, or filament-type (F), cathode. **b.** This drawing shows the structure of an indirectly heated cathode. The heater (twisted wire) receives power from a separate source, usually ac, and is insulated from the surrounding cylindrical cathode. In the symbol used for this type of cathode K stands for cathode and H for heater.

vacuum and gas-discharge tubes, the source of the electrons is termed the **cathode**, represented by the letter K. Hence, a tungsten-filament emitter is known as a *directly heated* or *filament-type cathode.* (See Fig. 14–4a.)

Many modern small vacuum tubes use indirect means to heat the cathode. Figure 14–4b shows the construction of an *indirectly heated cathode.* A tiny heating wire extends the length of a small tube whose outer surface is the emitter. The cathode surface is coated with a mixture of metallic oxides which improve its ability to emit electrons.

14–9 Emitted electrons must be replaced. As electrons are emitted from a hot cathode in a vacuum tube, they remove negative charges from it. As a result, the emitting cathode becomes positively charged. As emission continues, the electrode becomes increasingly positive and exerts more and more retarding force on the emitted electrons. If nothing is done about this, the emitting surface soon attracts back to itself as many electrons as it emits, so that the net emission is zero.

This can be overcome by connecting the cathode to a source of free electrons to replace those emitted. Such a source is supplied by the negative terminal of a chemical-electric cell or occasionally an electric generator.

Do It Now

Obtain discarded vacuum tubes and examine their interior. Metal tubes can be opened with a hack saw. Glass tubes should be wrapped in cloth or paper and broken in a vise or by taps from a hammer. Can you find directly and indirectly heated cathodes? (Battery-operated tubes are often of the directly heated variety.)

14–10 Emitted electrons can constitute a current in a vacuum tube. Even when the cathode of a vacuum tube is connected to a source of electrons, emission may not continue indefinitely. Very quickly a "cloud" of electrons occupies the space immediately surrounding the cathode. The negative charge of this cloud is called the **space charge** around the cathode. It tends to repel more emitted electrons back to the cathode, and hence would reduce net emission almost to zero.

However another electrode in the vacuum tube (called the **anode** or **plate**) is connected to the positive terminal of the dc source whose negative terminal is connected to the cathode. As a result, electrons are attracted toward the anode, creating a current in the tube. In typical vacuum

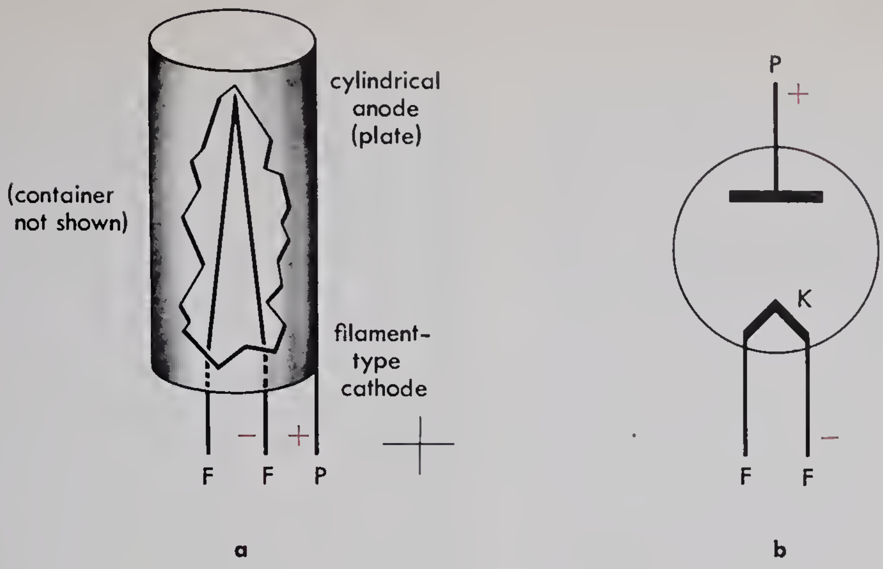


Figure 14–5 **a.** This diagram shows the actual construction of a typical two-electrode vacuum tube. **b.** This diagram is the symbol for a two-electrode vacuum tube used in circuit diagrams. In the use of symbols the emphasis is not on the physical construction but on the *function* of the parts.

tubes this electrode is a metal cylinder which surrounds the cathode, as in Fig. 14–5. As the plate-to-cathode potential difference is increased, it then offsets the effect of the space charge with increasing effectiveness.

Self Check

1. Why do free electrons need energy in order to be emitted from a conducting surface?
2. What is the meaning of the statement that the work-function of a given material is 3 electron volts?
3. How is energy supplied to electrons so they can be emitted?
4. What is the difference between directly heated and indirectly heated cathodes?
5. Why are cathodes often coated with metallic oxides?
6. What is a space charge? How does it affect electron emission?
7. How are electrons made to flow through a vacuum tube?

Problems

B The cathode material of a certain vacuum tube has a work-function of 1.8 eV. How much energy is required for emission in this tube where the total current is 40 milliamperes for an interval of 5.0 min?

Discussion Questions

1. Which electrons have more energy on the average, the free electrons in the wire leading to a vacuum tube cathode, or the electrons in the space charge around the cathode?
2. What would you expect to happen in a vacuum tube diode into which substantial amounts of air had leaked?
3. The potential difference between the two electrodes in a gas-discharge tube like that of Fig. 14–1 must be considerably higher than the potential difference between the cathode and anode in a thermionic tube. Why?

Diodes Rectify Alternating Current

14–11 A diode conducts electrons in only one direction. A vacuum tube containing two electrodes is called a **diode**. Under normal operating conditions, a diode conducts electrons from the cathode to the plate, as in Fig. 14–6a. In this case, the current is limited only by the internal resistance of the source of emf and by the internal resistance of the tube.

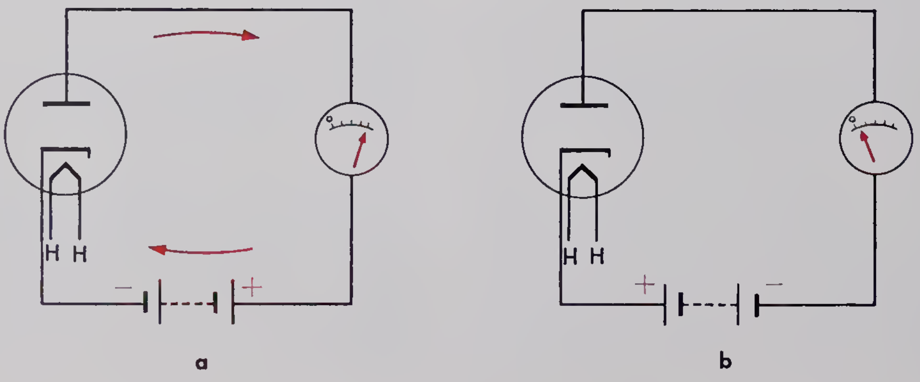
If the terminals are reversed, as in Fig. 14–6b, the heated and coated electrode is connected to the positive terminal of the energy source. Hence it has no supply of electrons and therefore cannot emit them. At the negative end of the energy supply is a plate which cannot emit electrons because only a very high potential difference can cause emission from a cold electrode.

The diode is a somewhat unique electric device. It conducts electrons when the heated and coated electrode is used as a cathode — that is, when it is connected to the negative part of a circuit — but not when it is connected in the opposite way. It acts as an electron valve which passes electrons in one direction only.

Although the plate (the cold electrode) of a diode vacuum tube must be positive with respect to the cathode (the heated electrode) in order for electrons to flow, the potential difference need not be great. Generally, some electrons will flow even though the plate-to-cathode potential difference is one volt or even less. In the tube just described, the current in the tube consists entirely of a flow of electrons from the cathode to the plate. Similar results can be obtained with tubes filled with gas at low pressure. In gas-filled tubes, however, the operation is more complex because ions move in both directions. A **thermionic diode** can now be defined as a two-electrode vacuum (or gas-filled) tube with a heated cathode.

14–12 A diode may act as a half-wave rectifier. The most important use of the two-electrode vacuum tube, or diode, is that of changing alternating current to direct current. This conversion is necessary for the operation of many modern devices. Most commercial electric power is supplied as alternating current, but direct current is needed for certain chemical processes, for charging storage cells, and for telephone circuits, among other things. Moreover, public address systems, radio and television receivers, and the like require direct current for proper operation. The conversion of alternating to direct current is called

Figure **14–6 a.** The cathode is negative with respect to the plate; therefore, the tube conducts electrons. **b.** The electrode polarity is reversed, and the tube does not conduct. This illustrates the rectifier action of a diode vacuum tube. The symbol for the cathode is for an indirectly heated cathode; the heater symbol is shown inside it.



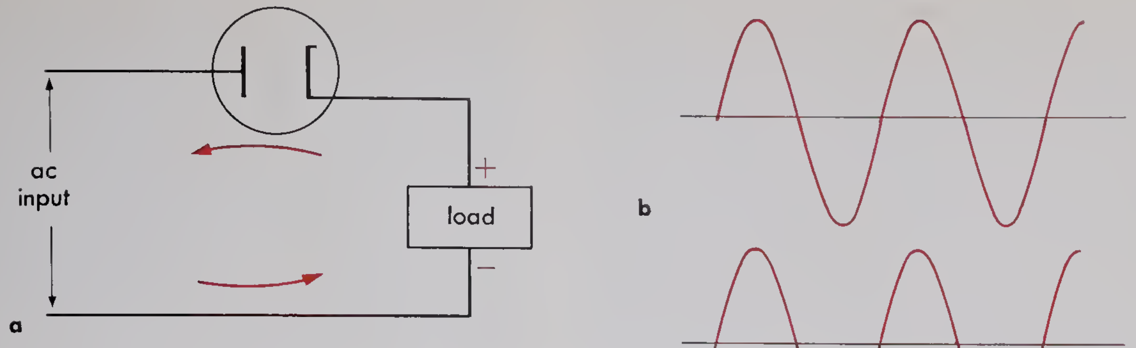


Figure 14–7 **a.** This diagram shows the connection of a diode into a simple half-wave rectifier circuit. Note that whenever a current exists, electrons move upward through the load; therefore, the bottom is negative with respect to the top. Notice that the heater symbol has been omitted in order to simplify the diagram. **b.** The sine wave represents the input wave form before it is rectified. Below it is the rectified wave form. It is unidirectional, but uneven and intermittent. For most uses it needs smoothing out or "filtering."

rectification; the diode tubes used to perform the task are called **rectifier tubes.**

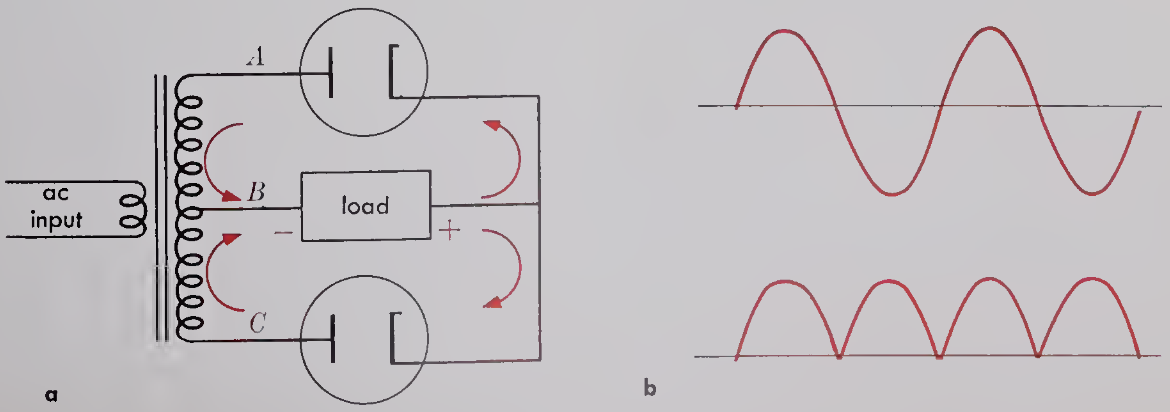
A simple rectifier circuit is shown in Fig. 14–7a. The part labeled "load" is the device which requires direct current for its operation. It might be a small phonograph amplifier or radio receiver. Since electrons pass through the rectifier tube in one direction only, the electron flow through the load is also unidirectional. However, the current in the load is intermittent. Because such a rectifier circuit utilizes only half the applied sine wave, it is called a **half-wave rectifier.** Many ac-dc radio receivers — that is, those designed to operate from either ac or dc electric supply lines — use half-wave rectifiers of this type.

14–13 Two diodes may function as a full-wave rectifier.

Most large radio receivers and hi-fi sets use a circuit known as a **full-wave rectifier.** Two diodes are used; one passing one half-cycle of the incoming ac wave-form and the other passing the other half. (See Fig. 14–8.)

Notice that the transformer in this circuit has a center-tapped secondary winding. This is a single winding which has connec-

Figure 14–8 **a.** This circuit shows how two diodes are connected into a full-wave rectifier circuit. During half the cycle the upper diode conducts, and during the other half cycle the other diode circuit takes over. No matter which diode is conducting, electrons flow from left to right through the load, as the arrows indicate. **b.** The top wave form is the incoming unrectified ac with the rectified output below it. The output of a full-wave rectifier is better than that of the half-wave rectifier because it is no longer intermittent; it is, however, still far from constant.



tions not only at each end, but also midway between the ends. You can think of this center-tapped winding as two identical secondary windings connected together. At any instant, the potential difference across *AB* is the same as that across *BC*. But what about the polarity of the potential differences? In Fig. 14–8a what is the polarity when *A* is 600 volts more positive than *C*? *A* is 300 volts more positive than *B*, and *B* is 300 volts more positive than *C*. If you trace these potentials around through the rest of the circuit, including the transformer secondary winding and the load, you find that the plate of the upper diode is positive with respect to its cathode. As a result, electrons pass through this tube, through *AB*, and from left to right through the load. In the lower tube, however, the plate is negative with respect to the cathode, so no electrons flow.

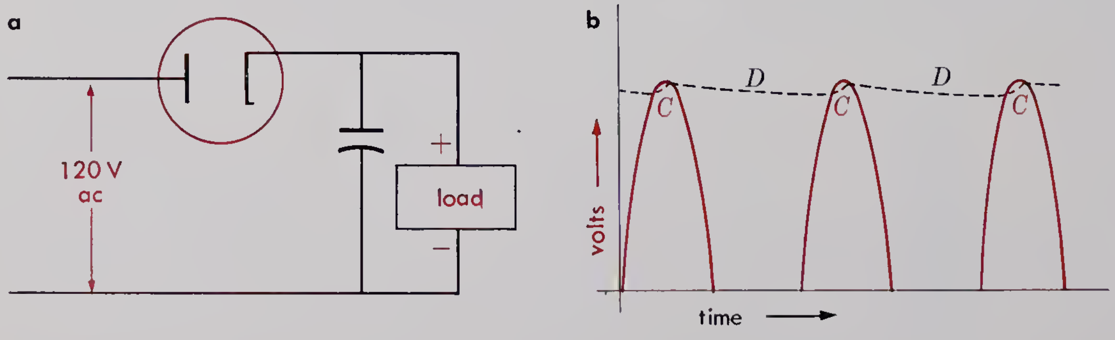
One half-cycle later (1/120 of a second for 60-cycle current) *C* is 300 volts positive with respect to *B* and *B* is 300 volts positive with respect to *A*. Under these conditions, the upper diode does not conduct, but the lower one does. Electrons flow from cathode to plate of the lower diode, through *CB*, and then from left to right through the load. Note that in both cases electrons pass from left to right through the load. This means that the current delivered by this full-wave rectifier is unidirectional, though, of course, fluctuating. Figure 14–8b is a graphical representation of the input and output wave-forms of the full-wave rectifier circuit.

14–14 A capacitor may act as a filter circuit. Although the half-wave and full-wave rectifier circuits of Figs. 14–7 and 14–8 provide unidirectional electron flow in the load, this rectified current is far from being pure direct current. Not only does it fluctuate in magnitude, it repeatedly falls to zero magnitude.

Since many loads require constant current, some arrangement must be made to smooth or filter out the irregularities in current supplied by a typical diode rectifier circuit. The circuit which provides this filtering action is known as a **filter circuit**.

An effective way to filter some of the irregularities from a half-wave or full-wave rectifier circuit is to use a capacitor, as in Fig. 14–9a. The capacitor is connected

Figure 14–9 a. In this diagram a filter capacitor has been added in parallel with the load. **b.** In this graph the solid lines are exactly like those on the bottom of Fig. 14–7b; they represent the potential difference across the load of an unfiltered half-wave rectifier circuit. The dotted lines represent the potential difference across the load of a half-wave rectifier circuit when a capacitor has been placed in parallel with the load. Notice that during the intervals marked *D* the capacitor slowly discharges, but it manages to maintain a nearly constant potential difference, provided the capacitor is large enough. During the intervals marked *C* the capacitor is charged by current through the diode.



directly across the load. A capacitor in parallel with the output of a rectifier circuit stores charge while the potential difference is high, and delivers the stored charge when potential difference would otherwise be low. The result is shown in the graph in Fig. 14–9b.

This capacitor filter is the simplest filter circuit. It converts the intermittent supply of Fig. 14–7 to the continuous, though still uneven, supply of Fig. 14–9b. The output of the circuit of Fig. 14–9b still has some irregularity in it. This unfiltered irregularity in the output of a rectifier-filter circuit is known as **ripple**.

Do It Now

The operation of a capacitor as a filter circuit has been compared to an emergency bank account. Funds are stored in the account when money is plentiful, drawn when money would otherwise be scarce or absent. To what extent do you consider this analogy valid? In what ways does it fail?

14–15 A fluctuating current can be analyzed into ac and dc components.

There is another way to look at the behavior of a capacitor as a filter circuit. A fluctuating direct current can be thought of as pure dc with ac added to it. This is illustrated in Fig. 14–10. Here a direct current of 50 milliamperes is added to an alternating current which varies from a maximum instantaneous value of 10 milliamperes in one direction to 10 milliamperes in the other direction. The sum of these two currents is a fluctuating dc which varies between 40 and 60 milliamperes. The same line of reasoning can be applied to fluctuating potential difference.

In a similar way, the current conducted by the unfiltered half-wave rectifier circuit of Fig. 14–7 can be considered as being composed of an ac and a dc component. True, the ac component is not a sine wave. Nevertheless, it is alternating current. Similarly, the potential difference across the load of a rectifier circuit, whether filtered or not, may be considered as a combination of ac and dc.

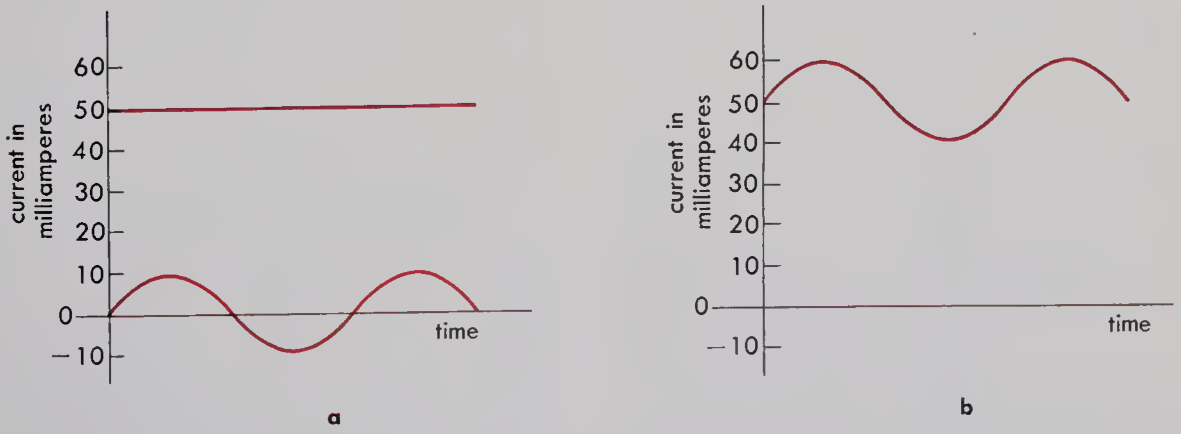


Figure 14–10 **a.** This graph shows a dc wave form of 50 milliamperes (mA) at the top and an ac wave form of 10 mA peak value below it. **b.** The wave forms of **a** are shown added together to make up a single current which fluctuates from a minimum of 40 mA to a maximum of 60 mA. By the reverse reasoning, a fluctuating current (or potential difference) can be considered as being made up of a dc component and an ac component.

Now look again at the simple capacitor filter of Fig. 14–9. The load circuit is really made up of two parallel branches, the load, and the capacitor itself. The load will pass either ac or dc; the capacitor passes ac quite readily, but does not pass dc at all. Therefore, most of the ac component goes through the capacitor, while all the dc component and a little of the ac goes through the load. Thus, relatively little of the ripple (which is ac) goes through the load. The capacitor filters most of the ripple from the output of the rectifier circuit.

14–16 Inductors can be used in filter circuits. The simple capacitor filter just analyzed is adequate for some applications. For most radio receivers and amplifiers, however, more thorough filtering of the rectifier output is necessary. This can be accomplished through the use of an inductor. A filter network employing an inductor and two capacitors is shown in Fig. 14–11.

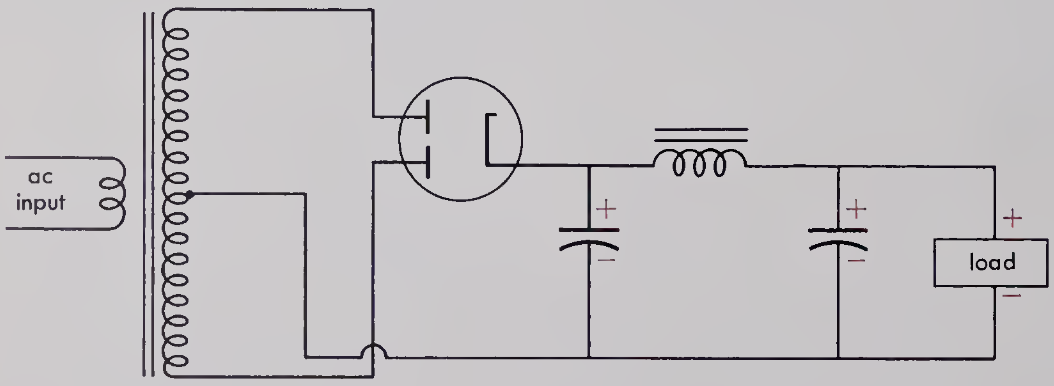
Remember the electron flow through the diode has an ac component and a dc component. An inductor opposes ac but passes dc quite readily. Much of the ac is in the capacitor branch on the left, partly because the capacitor offers such low opposition to ac and partly because the inductor offers high opposition to it. Therefore the current in the inductor is almost pure dc. Almost all of the remaining ac in the current from the inductor is in the second capacitor branch, rather than the load. The result of all this is to provide dc for the load, which for most purposes is sufficiently free of ac components or ripple.

14–17 Half-wave rectifier circuits differ from full-wave rectifier circuits. Both half-wave and full-wave rectifier circuits find wide use in modern electronic devices; each kind has its characteristic advantages. The more important of these are listed at the top of p. 343.

Self Check

1. Why cannot a diode vacuum tube conduct electrons from plate to cathode?
2. What is the most common application of diode vacuum tubes?
3. What happens to the "rejected" half of the sine-wave input in a half-wave rectifier?
4. What is meant by a center-tapped winding on a transformer?

Figure 14–11 This full-wave rectifier circuit is used in conjunction with a filter network. Notice that the circuit has been "stretched around" as compared with that in Fig. 14–8a. Note, too, that a dual-purpose diode has been used: two plates operating from a single cathode. This is possible because the two diodes of Fig. 14–8a have their cathodes fastened together.



Half-wave Rectifier Circuits	*Full-wave Rectifier Circuits*
1. Require no transformer, hence offer a saving in weight, size, and cost.	1. Presence of a transformer makes it easily possible to increase the potential difference of the output, merely by using a step-up or step-down transformer of the proper turns ratio.
2. Operate from dc power lines providing the rectifier is wired so that the cathode is connected to the negative side of the line. This is useful in ac-dc devices such as radios that can be used with either type of current.	2. Ripple frequency is twice as great (see Fig. 14–7 and 14–8). As a result, ripple can be filtered out with a filter network which is cheaper, lighter, and occupies less space than the filter needed for a half-wave rectifier.

5. In a simple capacitor used as a filter in a half-wave rectifier, during which part of the cycle does the capacitor acquire its energy?

6. Why does an inductor in a filter circuit tend to reject ripple?

7. Diagram each of the following circuits and then compare your diagrams with the appropriate ones in the text: half-wave rectifier circuit; full-wave rectifier circuit with two diodes; full-wave rectifier circuit with one diode having two plates; filter circuit with capacitors and inductor. Explain how each one operates.

8. Which kind of rectifier circuit should be used in an ac-dc radio?

Discussion Questions

1. Why cannot a full-wave rectifier circuit, as shown in Fig. 14–8, be operated without a transformer?

2. What are the frequencies of the ripple in a half-wave and in a full-wave rectifier circuit when used on a 60-cycle line?

Vacuum Tubes Can Amplify Electric Signals

14–18 The development of the vacuum tube amplifier was a great achievement. In 1883 Thomas A. Edison noticed that in one of his newly developed incandescent lamps a current could exist between the heated filament and a separate, unheated electrode, a phenomenon known as the **Edison effect.** You, of course, would call this a diode and would explain its action in terms of thermionic emission, electric fields, and space charge. Edison's ideas about it were much more vague, for the electron would not be discovered for another fourteen years. Evidently he noted the phenomenon with care, figured out the general idea of what was happening, recognized that the discovery needed further investigation, made detailed records of the entire observation, and then turned his attention to other developments in which he was engaged at the time.

The diode as you know it was developed in 1904 by the English engineer John A. Fleming. Because it permitted current in one direction but not the other, it was called the "Fleming valve." It was not until 1906 that the American scientist Lee De Forest made a profound improvement on the diode by adding a third electrode called the **grid** **(G)**. This was the birth of the **triode,** a vacuum tube (or gas-discharge tube) with three electrodes: a cathode, a plate, and a grid. A triode can amplify a variation in current or in potential difference.

Do It Now

Imagine that your knowledge of electricity is no more than that available in 1890. How would you explain the Edison effect? How would you explain the operation of a Fleming valve? Could you predict the function of a three-electrode vacuum tube?

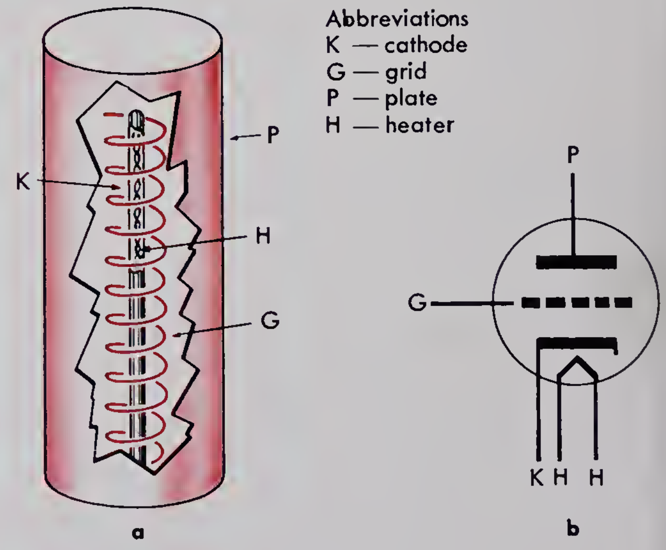
14–19 The grid controls the magnitude of tube current. The basic structure of a triode is shown in Fig. 14–12. The cathode is the slender cylinder along the axis of the tube, with the heater inside it. The outer cylinder is the plate. Wound in a spiral around the cathode is the grid. As you learn how a triode functions, keep these facts about the grid in mind:

1. The grid is not connected directly to either cathode or plate.
2. The grid is between the cathode and the plate.
3. The grid has only one connection.
4. The grid has relatively little metal in it. It is mostly space.

Imagine the tube of Fig. 14–12 with the plate positive, the cathode negative, and the grid not connected to anything. Electrons from the heated cathode are streaming toward the plate. Because the grid is mostly space, the electrons get through it very easily. Next, the grid is connected to the negative side of a battery, as shown in Fig. 14–13. First, it is made just slightly more negative than the cathode. Electrons emitted by the cathode are slightly repelled by the grid, and fewer of them reach the plate. As the grid is made more and more negative, fewer and fewer electrons manage to get by it. Finally, if the grid is sufficiently negative, the current through the tube is reduced to zero.

If the battery to which the grid is connected is now turned around so that the grid beoomes slightly more positive than the cathode, electrons are attracted. A few hit the grid and create a small current in the grid circuit, but most of them miss the fine wire of the grid and go on to the plate. The plate current increases. Thus you see

Figure 14–12 a. Diagram of a typical triode, showing the cathode (thin central cylinder), grid (spiral wire), and plate (outer cylinder). In an actual tube all of this is encased in a glass or metal envelope. Note that the grid is much closer to the cathode than the plate is. Consequently the grid potential has more influence on current through the tube than does plate potential. b. Symbol used for a triode.



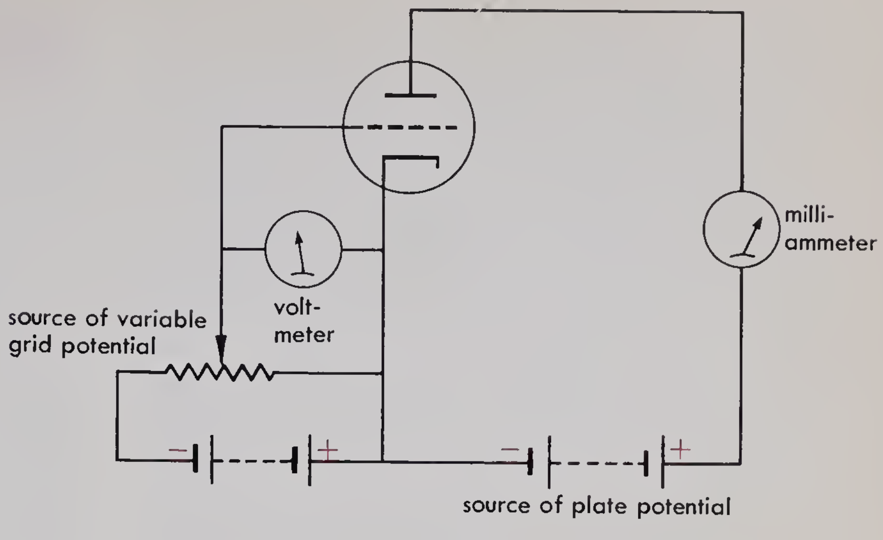


Figure 14–13 A circuit such as this illustrates the control that a grid has over tube current. Notice that a variable resistor permits grid-to-cathode potential difference to be varied. As the grid becomes more and more negative with respect to the cathode, current through the tube becomes smaller and smaller. As the grid becomes less negative than the cathode, the tube current increases. This relationship is shown graphically in Fig. 14–14.

that the magnitude of the potential difference between the grid and the cathode controls the current to the plate.

The grid control of the current through the tube is shown graphically in Fig. 14–14. Note that the variable which controls the magnitude of the current in the tube is the grid-to-cathode potential difference. Since the current in the tube is a flow of electrons out through the plate, this is commonly called the plate current, and abbreviated I_p. The grid-to-cathode potential difference is commonly called the grid voltage, and abbreviated V_g. Thus, V_g controls I_p.

There are thousands of kinds of multielectrode vacuum tubes. They vary in the amount of current they can handle, in their normal operating potentials, in their sensitivity, in their physical dimensions, and in many other ways. Many have four electrodes (tetrodes), five electrodes (pentodes), or even more. Some have two or even three separate sets of electrodes in the same evacuated enclosure.

Do It Now

Use the technique described on p. 336 to remove the electrodes from a triode. Can you find all the parts? How does the structure of the tube compare with that in Fig. 14–12?

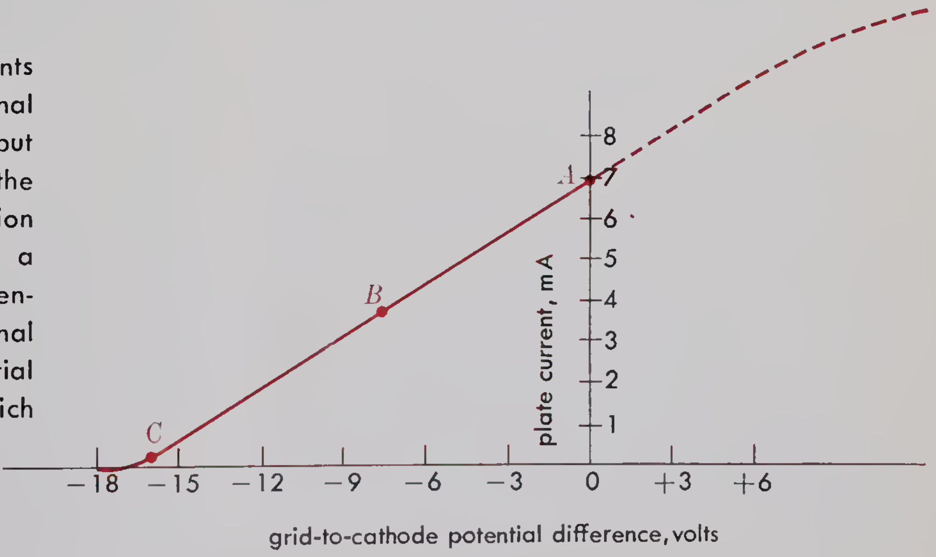


Figure 14–14 This curve represents the manner in which the input signal of a vacuum tube controls the output signal. Under typical conditions the tube is operated only on that portion of the graph between *A* and *C*, a portion of the curve which is essentially a straight line. When the signal is zero, the grid-to-cathode potential should be at point *B*, which is −8 volts.

14–20 Sound can be converted to electric energy and vice versa. Although you may speak of amplifiers as amplifying sound or making sounds louder, they actually do no such thing. The inputs and outputs of vacuum tubes and amplifier circuits are strictly *electric*. How then can amplifiers be used with the sound of hi-fi and magnetic tape, with the light of a TV picture, with bits of information as in computers and automation circuits, with radar and satellite research?

The answer is that any form of energy — sound, light, the movement of a car along an assembly line, or the signals from an orbiting satellite — must be converted to electric energy before it can be handled by electronic devices. A microphone takes incoming sound energy and translates the variations into a varying potential difference having the same frequency. A photoelectric cell absorbs incoming light energy, which produces a tiny electric current that fluctuates as the light becomes brighter or dimmer.

In an electronic device the pattern of energy variations is called a **signal**. If the signal is not already electric, it is converted into that form, then controlled by electronic circuits, and often finally converted back into some other form, such as sound and light in TV reception. The output of the electronic device is also called a signal.

Almost without exception, signals in electronics are ac phenomena. Even a simple turning off and on of a switch represents a change in current and potential difference. Many of the signals are nonsinusoidal, and many consist of an ac signal superimposed on dc, as discussed on p. 341. It is with these electric changes that communications electronics is concerned. Through electronics these signals are detected, measured, amplified, stored, or used to control something else.

Do It Now

How many different kinds of signals can you think of, not mentioned in the text, that are amplified or controlled by electronic circuits?

14–21 An input signal controls an output signal of greater magnitude. Consider the operation of a record player. The grooves in a record are wiggly lines. When the record turns with the needle in a groove, the needle is forced to wiggle back and forth. At the other end of the needle can be a coil of wire placed in the field of a magnet. As the coil wiggles, a fluctuating emf is induced, having the same pattern as do the wiggles in the record groove. A phonograph pickup thus converts the mechanical energy of vibration of the needle into electric energy. If you were to connect earphones directly to the phonograph pickup, you would hear a very faint sound, as the fluctuating electric current causes the diaphragm in the earphones to vibrate.

If you wish to have a louder sound, you must add an amplifier, as shown in Fig. 14–15. Here the signal from the phonograph pickup is the input and the sound you hear in the earphones is the output. The input is connected to the grid. Notice that the other terminal of the pickup is connected indirectly to the cathode. As a result, the generated emf of the pickup is actually a grid-to-cathode potential difference, which varies with the input. As this grid-to-cathode potential difference fluctuates, it produces a corresponding fluctuation in the electron flow from cathode to plate. The operation of the tube is such that a small signal at the input can control a large signal at the output. Hence, the circuit *amplifies* the signal.

In most cases, you want the output signal of an amplifier circuit to be exactly like the input signal — only larger, of course. That

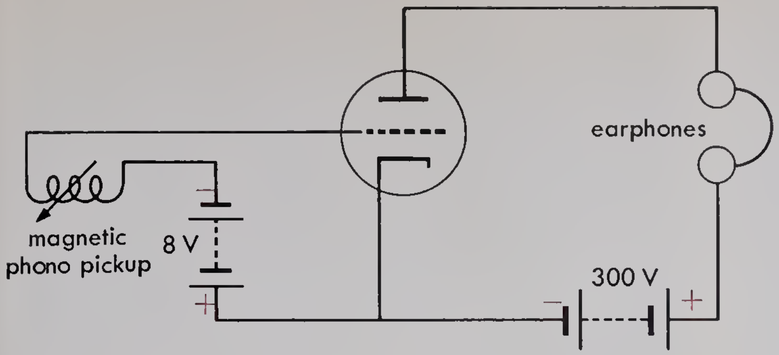


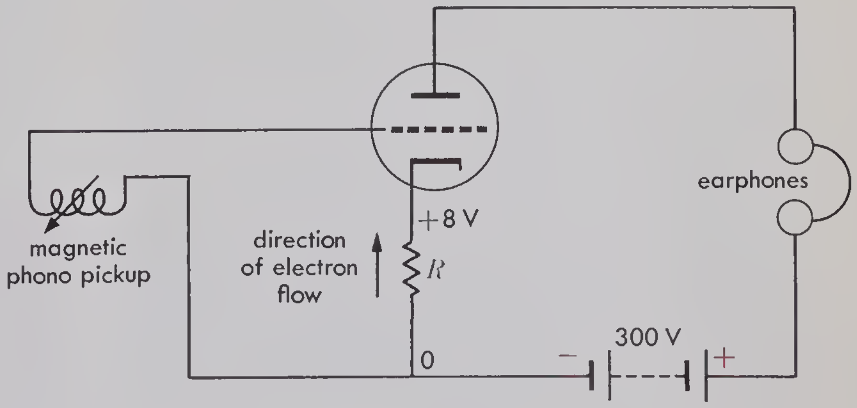
Figure 14–15 A simple one-tube amplifier, using the tube of Fig. 14–14. So that the signal will be free of distortion, the grid must, on the average, be 8 V more negative than the cathode. The 8-V battery provides the necessary grid bias.

is, you want amplification, but you do not want distortion. You can see what the circuit requirements are with the help of Fig. 14–14. Not all the curve in the graph can be used. Any part which is seriously curved, like that at the extreme left, will produce distortion. Furthermore, in most circuits, the grid should never be permitted to become more positive than the cathode. If it does, the grid acts like a plate and draws electrons from the cathode, thus upsetting the tube's operation. In Fig. 14–14, then, you can operate only between points *C* and *A* if you wish distortion-free amplification of the signal.

The way to operate in the region from *C* to *A* is to design the circuit so that when there is no signal present at all, the grid is 8 volts negative with respect to the cathode. This is point *B* on the graph of Fig. 14–14 — just halfway between *A* and *C*. Now you can put a signal on the grid that fluctuates between zero volts at its upper extreme and −16 volts at its lower extreme. This kind of measure of fluctuation, from one extreme, or "peak," to another is called the **peak-to-peak value**

14–22 Proper grid bias can be provided through suitable circuit design. In the discussion above, you found that for the particular tube graphed in Fig. 14–14, it is necessary to arrange the circuit so that when there is no signal present, the grid is 8 volts negative with respect to the cathode. For other kinds of tubes, the magnitude of this grid-to-cathode voltage is different, of course. But the grid voltage at point *B*, whatever it is, is known as **grid bias**. One way to provide proper grid bias for a one-tube amplifier would be to use an 8-volt battery as shown in Fig. 14–15. However, proper bias can be provided without the use of a battery of electric cells. A superior method of doing this is the one in Fig. 14–16. The key component in this circuit is the resistor in the cathode circuit. Its resistance is such that the average tube

Figure 14–16 This amplifier circuit is just like that of Fig. 14–15 except that the grid bias is provided by the IR drop in the resistor in the cathode circuit instead of by a battery.



current in it sets up an *IR* drop of 8 volts ($V = IR$ according to Ohm's law). Furthermore, the direction of electron flow is such as to make the top of this cathode resistor positive with respect to the bottom. Hence the cathode of the tube has an average potential of +8 volts with respect to the line at the bottom of the circuit.

Now notice that one terminal of the pickup is connected to the grid and the other to the bottom of the cathode resistor. This means that when there is no signal, the grid is at zero potential. Therefore, the cathode is 8 volts more positive than the grid, which is another way of saying that the zero-signal grid-to-cathode potential is −8 volts. This meets all the conditions necessary for proper tube bias. This is known as cathode-resistor bias and is by far the most common bias circuit in use today.

14–23 Amplification is consistent with the conservation of energy. Many students are confused by the idea of electronic amplification. How can you make big signals from little ones, how can you "get something for nothing?" You cannot, and you do not.

The fact is that vacuum tubes and transistors are *control devices.* A rough analogy is the light switch on the wall. You use perhaps a watt of power to flip the switch; the lights go on. The lights may represent from a few watts to thousands of watts. Has all this power been transformed from the effort of your finger? Of course not. Your finger has merely controlled energy from another source, in this case the electric power company.

Similarly, a little power expended as your foot pushes down on the accelerator of a car controls scores of horsepower from the engine. In electronics, a little energy at the input — the grid circuit — can control a much larger supply of energy at the output — the plate circuit.

14–24 One amplifier stage can feed another. A single vacuum tube and its associated amplifier circuit is known as a **stage** of amplification. Since the output of a vacuum tube is an electric signal, it can be used as the input signal for another stage of amplification. There are many kinds of circuit used to connect, or couple, the output of one amplifier stage to the input of the next stage.

An amplifier's ability to amplify signals is commonly called its **gain**. Gain of an amplifier is the ratio of output to input signal, both expressed in the same units. For example, if a stage of amplification has an input signal of 2 volts and produces at its output (or at the input to the following stage, if there is one) a signal of 24 volts, the gain is 24 volts/2 volts = 12. When two or more stages of gain are coupled one to the next, the total gain is the product of the individual gains.

Self Check

1. Who developed the first useful diode? The first useful triode?
2. Why is the control grid of a vacuum tube mostly space?
3. What changes in the grid circuit of a triode produce corresponding changes in plate current?
4. Why is it desirable for the grid to be negative compared with the cathode?
5. Explain the statement: Audio amplifiers do not amplify sound.
6. Why is amplification by a vacuum tube not a violation of the law of conservation of energy?

Problems

A 1. The following data are taken from the straight-line part of the input-output graph of an amplifier tube. The tube draws 12 milliamperes plate current when the grid is 4 V more negative than the cathode. When the grid potential with respect to the cathode is −6 V, plate current is 9 milliamperes. What is the plate current when grid potential is −10 V with respect to the cathode?

2. A signal with a fluctuation of 1.6 V at the input of one stage of a certain vacuum tube amplifier produces a signal with a fluctuation of 24 V at the output of that stage. What is the gain of the stage? What is the gain of a three-stage amplifier consisting of three such stages connected to each other, one after the other?

Discussion Questions

1. Why is the grid of a triode placed so much closer to the cathode than is the plate?
2. Why does not the grid of a vacuum tube ordinarily draw a substantial current of electrons?

Chapter Summary

At low pressure and in reasonably high electric fields, gases ionize into positive and negative ions. The negative ions are electrons, and the positive ions are atoms with some electrons removed. These charged ions move because they are in an electric field; they constitute a current in a gas. As electrons strike atoms in their path, they dislodge orbiting electrons of those atoms into larger, higher-energy orbits. When the orbiting electrons return to their usual orbit, they give off the energy they gained in the larger orbit in the form of visible light or invisible radiations. Fluorescent lamps are gas-discharge tubes in which most of the energy released by the gas is invisible radiation. This strikes special chemicals, or phosphors, on the inside of the tube and excites them to give off visible light.

Hot metals emit free electrons. This thermionic emission can be enhanced with higher temperatures and by proper selection of emitting material. To get continuous emission, the emitted electrons must be replaced, and they must be removed from the vicinity of the emitter. When these requirements have been met, a current of electrons exists in a vacuum tube. A cathode may be heated by a nearby but separate heater; the cathode may itself be a heated filament.

Thermionic diodes conduct electrons in one direction only, from the hot, relatively negative cathode toward the cool, relatively positive anode, or plate. The principal use of diodes is in rectifier circuits. When ac is rectified to dc, there remains some ripple in the output. This can be removed by means of filter networks made up of inductors and capacitors. The behavior of these networks can be understood by considering a fluctuating direct current to be composed of an ac and a dc component.

Triodes have a third electrode — a control grid — between the cathode and the plate. Variations in the potential difference between grid and cathode produce corresponding variations in the plate current of the tube. The triode is thus a control device. Triodes are purely electronic devices; they handle only electric signals. Hence, signals which represent sound or light or other energy forms must be converted to electric signals before they can be handled by triodes. Since a small signal at the input of a triode can control a larger signal at the output, the tube and its associated circuit is capable of amplification. Amplifier circuits must be designed so that the tube operates only over the desired portion of its total range. One aspect of proper circuit design is to provide proper tube bias so that the potential on the grid never goes more positive than the cathode, nor more negative than a point at which no electrons will flow. The gain of an amplifier, or of a stage of amplification, is the ratio of its output to its input, both expressed in the same units. Stages of amplification can be connected to one another. The gain of a multistage amplifier is equal to the product of the gains of its successive stages of amplifications.

Vocabulary

electrode (*p. 332*)
fluorescent lamp (*p. 334*)
fluoresce (*p. 334*)
phosphor (*p. 334*)
vacuum tube (*p. 335*)
thermionic emission (*p. 335*)
work-function (*p. 335*)
cathode: directly heated, filament type; indirectly heated (*p. 336*)
space charge (*p. 336*)
anode, plate (*p. 336*)
diode (*p. 338*)
thermionic diode (*p. 338*)
rectification (*p. 339*)
half-wave rectifier (*p. 339*)
full-wave rectifier (*p. 339*)
filter circuit (*p. 340*)
ripple (*p. 341*)
Edison effect (*p. 343*)
grid (*p. 344*)
triode (*p. 344*)
plate current (*p. 345*)
signal (*p. 346*)
input, output signal (*p. 346*)
amplification, amplifier (*p. 346*)
peak-to-peak value (*p. 347*)
grid bias (*p. 347*)
gain (*p. 348*)

Discussion Questions

1. Why must a gas be ionized before it can conduct current?
2. Considerable research has been carried out to find phosphors which will continue to fluoresce for at least a short time after their exposure to ultraviolet light ceases. Of what advantage would this be in fluorescent lamps?
3. Many other metals have lower work-functions than does tungsten. Why cannot these also be used as emitting filaments?
4. The tube in Fig. 14–11 contains three electrodes. Why, then, is it possible to call it a diode?
5. Why is it not customary to speak of the input to a vacuum tube amplifier circuit as a signal current?

Work on Your Own

Many students like to build radio receivers or other electronic devices. For their benefit, here is a list of reference material.

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PHYSICS HALL OF FAME

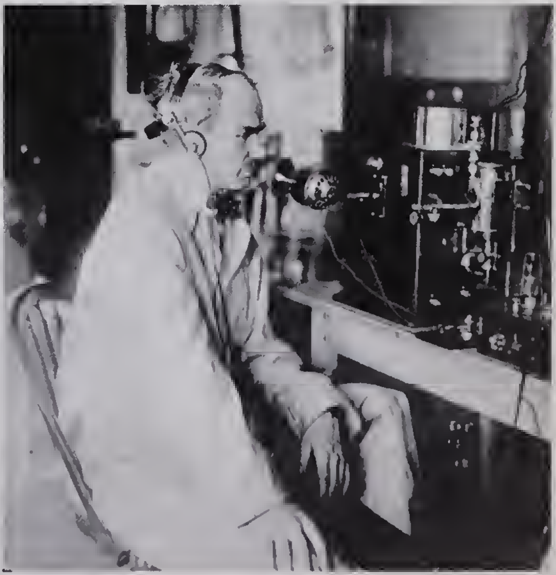
Lee De Forest · 1873–1961

More than any other scientist, the American inventor Lee De Forest was responsible for the basic developments which underlie the science and technology of modern vacuum tubes. In 1883 Edison showed that an electric current (now called the Edison effect) could exist between a heated filament and a metal plate, both enclosed in a vacuum. In 1904 the English physicist John Flemming found that such a two-electrode vacuum tube (diode) could detect wireless signals. When De Forest finished his doctoral degree at Yale, specializing in radio waves, he resolved to excel in the new field of wireless communications. To the basic diode vacuum tube De Forest added a third electrode, which could control the magnitude of current between the other two. This control electrode eventually took the form of a zig-zag grid of wire between the hot filament and the cool, metal electrode.

De Forest's basic three-electrode vacuum tube — the triode — was patented in 1906. The following year he patented the use of a triode in an amplifier circuit. Five years later he showed that the tube could also operate as an electronic oscillator to produce high-frequency alternating currents.

De Forest sought to develop a business enterprise on the basis of his vacuum tube developments, but he was less successful as a business organizer than as a pioneer in electronics. In the early years the usefulness of his triode was severely ridiculed. In 1913 he tried to sell stock in a long-range communication system which used the triode, and he was actually brought to trial for fraudulent use of the mails. The prosecution argued (unsuccessfully) that the triode was a fake and would not really work. Yet two years later the triode was successfully used for radiotelephone communication between Virginia and Paris and between Virginia and Honolulu. Eventually the American Telephone and Telegraph Company purchased the patent rights to many of De Forest's inventions.

Between 1902 and 1952 De Forest took out more than 300 patents, including some related to sound-on-film motion pictures, radiotelephony, photoelectric cells, and color television.



CHAPTER 15

Official U.S. Navy Photograph

Radio telescopes are used to detect radio waves from celestial bodies and from man-made space vehicles. The parabolic reflector, here 84 feet in diameter, focuses the incoming waves on the instruments in the small cylinder in the center.

Communication Through Electronics

Most people take modern electronics communication for granted — they also take it for granted that electronics communication consists of only radio and television. But what about these situations?

A jazz enthusiast plays a favorite selection on a record player or on a tape recorder.

An airplane pilot uses his electronic navigational equipment to determine his exact location on a foggy night.

A small boy flies a model airplane by radio remote control.

An unmanned satellite automatically sends back scientific data concerning radiation in space.

A radar installation at a remote defense outpost scans the sky for unseen objects, friendly or otherwise.

These, too, are examples of communication through electronics.

In this chapter you will learn something about radio and television, about antennas and radio waves, about amplifiers, and about telemetering. You will not learn all the details about these systems, nor how to design or repair them. Rather, you will begin to understand the basic fundamentals of communications electronics, and you will also reinforce your understanding of physics in general.

Transducers

15–1 A transducer converts energy. Although you commonly refer to a hi-fi amplifier as amplifying *sound*, in reality it uses a small *electric* signal to produce a larger *electric* signal. These input and output signals are patterns of changes in electric current, potential difference, magnetic field, and the like. This is true in the telephone, in radio, and in the audio signal of TV, and in sound recorded on disc, magnetic tape, or on film, as in sound motion pictures.

When a sound signal is changed to an electric signal, there is, of course, a change from one energy form to another, but this is not all. A signal is a *pattern of variations* of something — movement, magnetism, brilliance of light, current, or potential difference, for example. As the energy change occurs, the *pattern* of variations must be preserved; otherwise distortion results. If the pattern of variations remains the same, you say the *signal* is the same, regardless of whether the pattern is in electric current, magnetism, sound, or some other form.

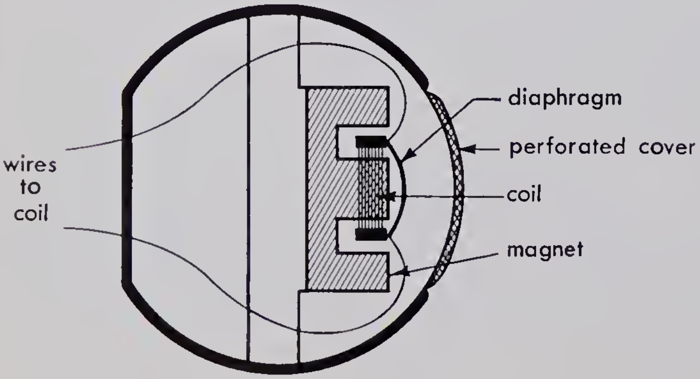
In electronics the devices that serve to convert signals from one form of energy to another are called **transducers**. There are many kinds of these devices; you are already familiar with several of them.

15–2 Phonograph pickups and microphones are often magnetic transducers.

Phonograph pickups are transducers. One kind of phonograph pickup in common use is really a small electric generator. The needle vibrates in the record grooves and causes parts of the pickup mechanism to move in a magnetic field, generating a signal emf whose pattern corresponds to the recorded sound.

The microphone in Fig. 15–1 is representative of magnetic transducers. A miniature coil of wire is fastened to a lightweight and very flexible diaphragm. When sound waves strike the diaphragm, they set it in motion, and the coil vibrates back and forth in the magnetic field, generating an emf.

Figure 15–1 This microphone is a magnetic transducer that converts a sound signal to an electric signal. Sound entering through the perforated cover causes the coil in the microphone to vibrate across a magnetic field, thus generating an emf.

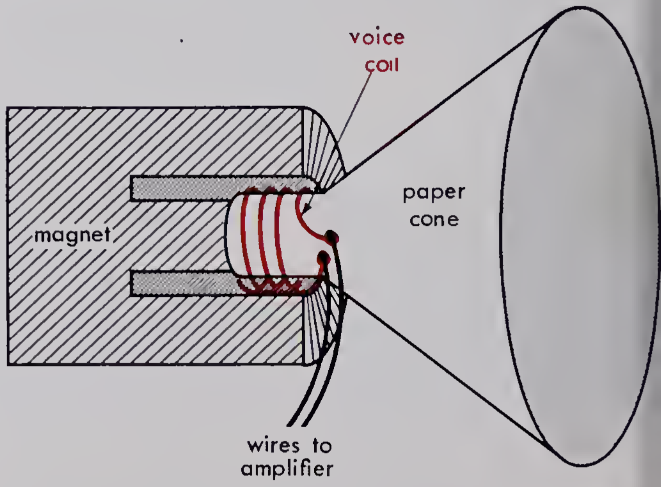


15–3 Speakers operate on the motor effect.

The earpiece of a telephone is a familiar example of an electric-energy–to–sound transducer. Household radios, TV sets, and record players use loud-speakers. This term is a hold-over from the early days of radio when loud-speakers were introduced to replace the older earphones, which were really "soft speakers." Loud-speakers are now called simply *speakers*.

The **dynamic speaker** is the most common type used today. It is really a special kind of electric motor. The coil consists of a few dozen turns of copper or aluminum wire wound around a hollow cylinder and free to move back and forth in an intense magnetic field, usually provided by a permanent magnet or by an electromagnet. As current fluctuates in this "voice coil," the coil responds to the motor effect and moves back and forth in accordance with the signal. A paper cone several inches in diameter is fastened to the voice coil cylinder. It moves as the voice coil moves, and since its vibrations set air molecules in motion, it increases the intensity of the sound produced (Fig. 15–2).

Figure 15–2 A dynamic speaker operates on the same principle as an electric motor. When an alternating signal current exists in the coil of wire, the coil vibrates in the magnetic field of the permanent magnet. The paper cone is thus forced to vibrate, producing a sound.



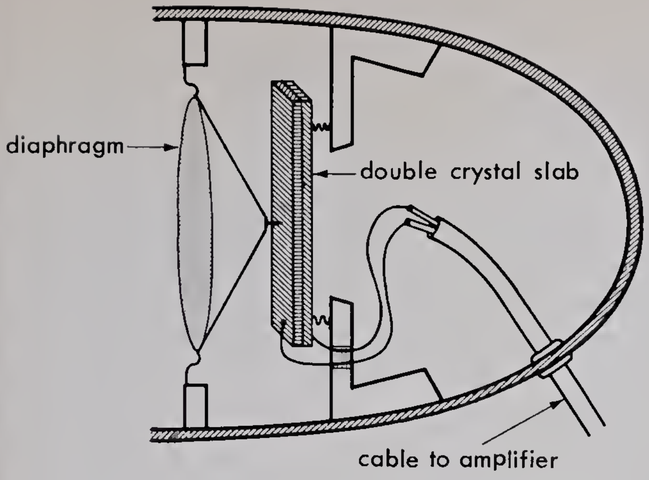


Figure 15–3 In a simple, crystal microphone sound vibrations make the diaphragm vibrate. The vibrations in turn make the double piezoelectric-crystal slab bend slightly, producing a varying emf with the same frequency and wave form as the sound.

15–4 Some transducers are not magnetic. Although magnetic microphones and phonograph pickups are common and reliable, they are not the only kinds of transducers in use in modern audio circuits. One very popular transducer utilizes the **piezoelectric effect** by which certain crystals and certain ceramic (glass or porcelain-like) materials, when bent or twisted, generate a small but definite emf. Such a crystal can be incorporated in a microphone or phonograph pickup (Fig. 15–3); these are referred to as *crystal microphones,* or *crystal pickups.*

The piezoelectric effect can also be used in an electricity-to-sound transducer. An electric signal, applied to a suitable crystal, causes the crystal to vibrate, producing a corresponding sound signal. Crystal earphones are fairly common in electronics work.

15–5 Some transducers involve energy forms other than sound. While sound is the most common signal for electronics communication devices, it is not the only one. In television and in wirephoto systems a picture exists as a pattern of bright and dim light. A transducer converts this brilliance pattern into an electric pattern, usually called a **video signal.** In this form it is amplified and controlled, broadcast and received, and amplified some more. Finally another transducer — the TV picture tube — converts it again to a pattern of light intensity.

Temperature-sensitive resistors can transduce temperature readings to electric signals so they can be communicated from the blast furnace to the control room, or from an artificial satellite to the earth.

A G-M counter is a transducer which converts the impulse of radiation to an electric signal.

Radio transmitters transduce electric signals into corresponding radio waves, and receiving antennas transduce them back to electric signals. Without transducers, radio communication would be impossible.

Self Check

1. What is a transducer?
2. In what form is the signal on a phonograph record?
3. Describe the operation of a dynamic speaker.

Discussion Questions

1. The electric signal delivered by a phonograph pickup to an amplifier contains a small but distinct quantity of energy. What is the source of this energy?
2. In the magnet of the dynamic speaker in Fig. 15–2, the solid cylinder inside the moving coil may be considered to be one pole. Where is the other pole?
3. Piezoelectric phonograph pickups are free of one of the serious problems possessed by magnetic-type pickups. The latter must be well shielded from the electric motors which drive the turntable. Why is this unnecessary with piezoelectric pickups?

Radio Waves

15–6 Vibrating electric charges produce changing electric and magnetic fields. You know that radio and TV signals travel through space without the aid of tubes, wires, or even air. To understand radio communication, you need to know something about the radio waves which carry the signals. You may remember that **radio waves** are one kind of electromagnetic wave. Radio waves are produced by vibrating electric charges. As you know, an electric charge is surrounded by an electric field. If the charge moves, the field moves; if the charge vibrates, the field vibrates. In addition, a moving charge produces a magnetic field, and the direction of the field depends on the direction of motion of the charge. Hence a vibrating charge produces a vibrating magnetic field. To sum it up, a vibrating electric charge produces simultaneously vibrating electric and magnetic fields.

15–7 Electromagnetic waves are radiated through space. Figure 15–4a shows what happens in a radio antenna of the kind used by broadcasting stations. In the antenna, electrons oscillate back and forth, so that the upper end of the antenna is first negative and then positive. At the instant shown in the diagram, the upper end is negative making the lower end relatively positive. As a consequence, an electric field surrounds the antenna. The shape of the field is something like the ribs of a huge umbrella. At the same time there is a magnetic field around the antenna, because electrons are moving downward. The magnetic field takes the form of horizontal circles around the antenna. The important thing to note here is that at any point the two fields are at right angles to each other.

As electrons surge first upward and then downward in the antenna, the electric field and the magnetic field both change in mag-

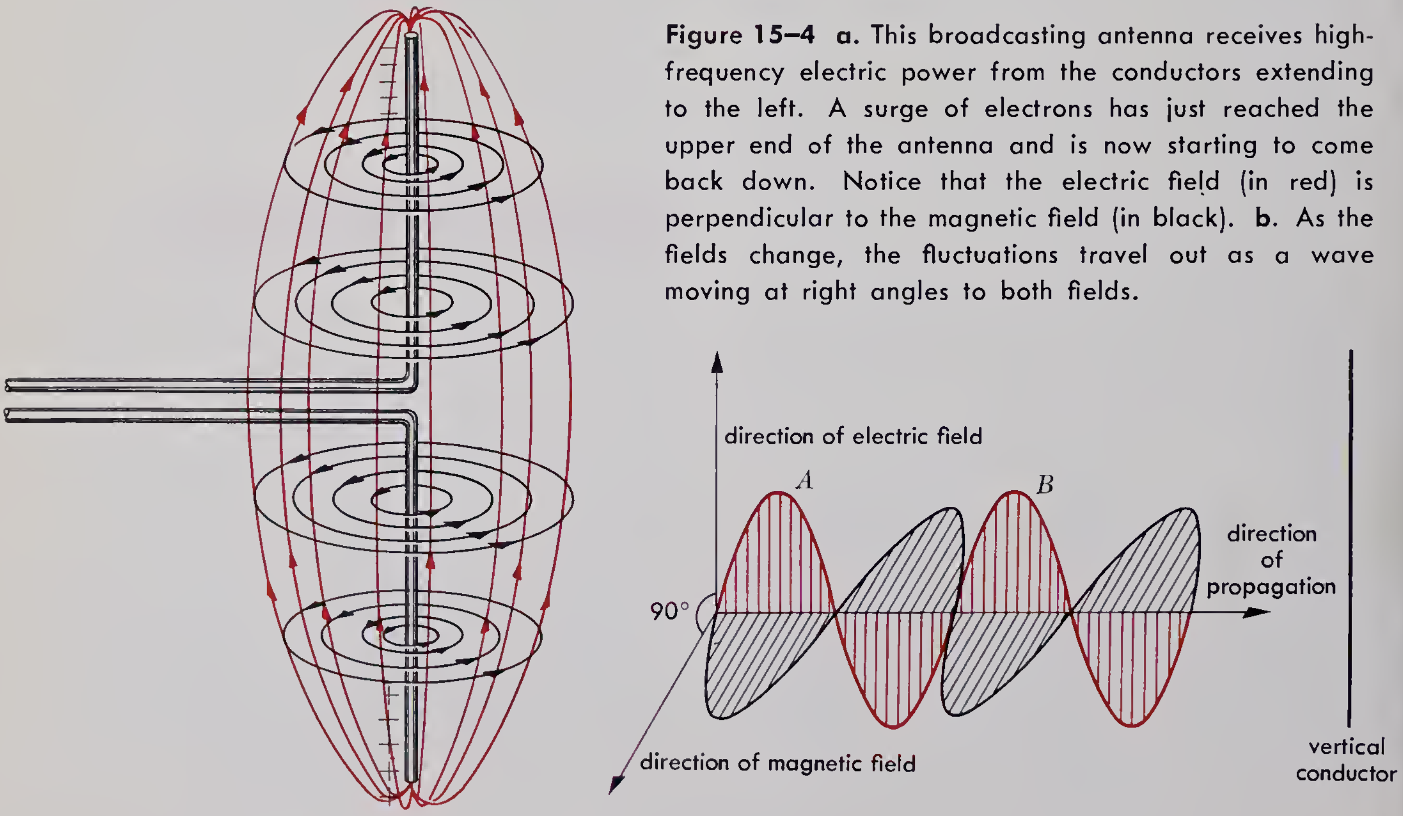


Figure 15–4 a. This broadcasting antenna receives high-frequency electric power from the conductors extending to the left. A surge of electrons has just reached the upper end of the antenna and is now starting to come back down. Notice that the electric field (in red) is perpendicular to the magnetic field (in black). **b.** As the fields change, the fluctuations travel out as a wave moving at right angles to both fields.

a

b

nitude and direction, but remain at right angles to each other. Theoretically both fields extend infinitely far in all directions. However, when the fields change, they do not change everywhere at the same time. Instead, the changes travel out from the antenna, much as ripples travel out from the place where a stone drops into a pond. The traveling changes in the fields are called an **electromagnetic wave**. The wave travels at right angles to both fields, as shown in Fig. 15–4b. The speed with which the wave travels in a vacuum is 1.86×10^5 mi/sec, or 3.00×10^8 m/sec. The speed in air is very slightly less.

15–8 Electromagnetic waves induce an emf in a conductor. When an electromagnetic wave strikes a conductor such as a receiving antenna, a varying magnetic field moves past the conductor. This is a situation much like that in an electric generator. Hence you should not be surprised to learn that the electromagnetic wave induces an emf in the conductor. At the same time, the electric component of the wave constitutes an alternating electric field in the region of the conductor. This field also tends to make electrons in the conductor move. Consequently, both the magnetic and the electric components of an electromagnetic wave are such as to make free electrons vibrate. Thus, the electromagnetic wave induces an emf in any conductor which lies in its path.

Notice that the induced emf is due both to the alternating magnetic field and to the alternating electric field which make up the electromagnetic wave. If the conductor in which the emf is induced is part of a complete circuit, as in the case of a radio antenna, a current results. The electromagnetic wave gives up a small quantity of energy to each particle which it moves.

High-frequency, high-power energy is fed to the transmitting antenna by electronic circuits. Here the energy is converted to electromagnetic waves, which radiate out in all directions. At the receiving end, a similar but usually much smaller antenna "picks up," or receives, the electromagnetic waves and converts them back into high-frequency electric energy. The energy received may be less than one billionth of that originally radiated by the transmitting antenna, but it can be amplified and controlled by the circuits in the receiving set.

Modern broadcasting stations vary from those whose useful range is only a few feet up to the special military units which broadcast and receive radio signals from artificial satellites far out in space. The typical commercial broadcast station usually has a range of several hundred miles. The frequencies used by most commercial broadcasting stations are from 540 to 1600 kilocycles per second. (One kilocycle per second, abbreviated kc, is 1000 cps. Note that the abbreviation may omit any symbol for "per second.") Amateur radio, police and aviation communication, television, and radar use other frequencies ranging from about 100 kc up to thousands of megacycles per second. (One megacycle per second, abbreviated Mc, is 1,000,000 cps.)

15–9 Speed, frequency, and wavelength are related by a simple formula. In a previous course you studied the wave nature of sound and light; a little review here might be in order. The frequency of a wave motion, or of its source, is the number of complete cycles of motion it undergoes each second. In the traveling wave, the wavelength is defined as the distance between any point on the wave and the next point which corresponds exactly to it. This is clear in Fig. 15–4b, where the distance from *A* to *B* is 1 wavelength. A simple mathematical relationship exists between the velocity of a wave, its frequency, and its wavelength. This relationship is:

$$v = f\lambda$$

where v is the velocity of wave travel, f is the frequency of wave motion, and λ is the wavelength. This relationship holds for waves in general, including electromagnetic waves.

The frequencies of radio waves are usually given in kilocycles per second or megacycles per second. Wavelengths are usually measured in meters, although very short ones are often specified in terms of centimeters or even millimeters.

15–10 Audio frequencies are not practical for electromagnetic radiation. You already know that a sound signal can be converted to an electric signal, and can then be amplified and controlled electronically. Why, you might ask, cannot a sound be converted to an audio-frequency electric signal, radiated into space by a transmitting antenna, received on another antenna, amplified, and heard? Here are the reasons why the problem of radio communication cannot be solved so simply:

1. While electromagnetic waves (radio waves) can exist at audio frequencies (frequencies equal to those of audible sound), they require enormous power and very large equipment.
2. Frequencies of 100 kc and up, which are practicable for electromagnetic radiation, are far beyond the range of human hearing. These are called **radio frequencies (rf).**
3. An audio signal contains a great range of frequencies: 300–3000 cps for understandable voice, 20–20,000 cps for music. However, for good control and efficiency, an electromagnetic wave should be at a single frequency, or within a narrow band of frequencies.
4. Even if electromagnetic radiation were practicable at audio frequencies, only one signal at a time would be possible in a given location; more than one would interfere with each other.

Do It Now

Look at the dial of a home radio. What frequency range does it cover? What frequencies are covered by a frequency-modulated radio? How do these compare with audio frequencies? Why is there a difference?

Self Check

1. In an electromagnetic wave, what is the relation among the directions of the electric field, the magnetic field, and the wave travel?
2. When an electromagnetic wave induces an emf in a conductor, is this action due to the magnetic field, the electric field, neither, or both?
3. What is the source of the energy which exists in your antenna when you are receiving a radio signal?
4. If the vibrating electric charges in a transmitting antenna are caused by a 3.5 Mc sinusoidal ac, what do you know about the frequency and the wave-form of the magnetic field and electric field which the antenna radiates?
5. What is considered the range of audio frequencies for good reproduction of high fidelity music?

Discussion Questions

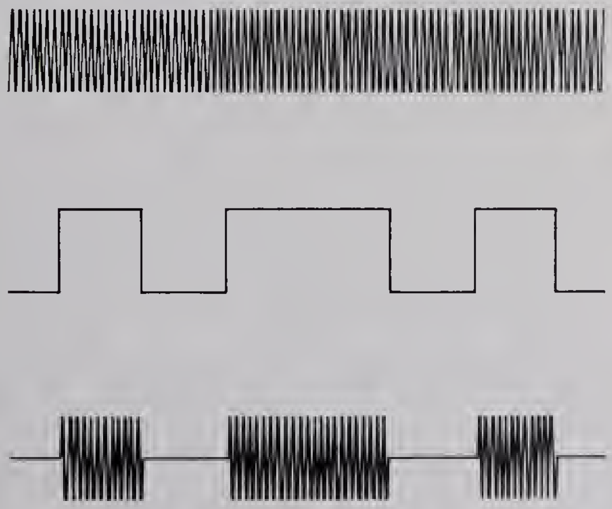
1. Why are not all electric fields accompanied by a magnetic field, as is the case with electromagnetic waves?
2. Electromagnetic waves of suitable strength and frequency produce distinct heating effects in conductors; this is the basis for induction heaters and induction furnaces, also diathermy. Can you explain how a strong electromagnetic field heats a conductor which it strikes?

Amplitude and Frequency Modulation

15–11 Carrier amplitude can be modulated by an audio signal. If a radio wave at audio frequencies is not practicable, and if the high frequencies that are practicable are not in the audible range, how is radio possible? The Italian scientist Marconi, usually considered the father of wireless communication, solved this problem very simply. He sent out a high-frequency wave and interrupted it according to the telegraph code, which had already been developed by Morse. Marconi then devised a receiving unit which would reproduce the "on-ness" and "off-ness" in terms of sound and silence. Thus the operator at the receiving end could read the coded message that had been transmitted through electromagnetic radiation.

This system, clever and useful though it is, is scarcely suitable for broadcasting voice or music. It is limited to the use of some kind of code. It is fruitful, however, to consider this system as the actual combination of two different signals, as in Fig. 15–5. At the top of this illustration is a sine wave of 1,000,000 cps. This high-frequency radio wave is called the **carrier wave**, or the **carrier**. Its frequency is high enough and its power strong enough that it can be broadcast over very great distances. The middle portion of the diagram is the telegraph code for the letter *R*. It appears as an intermittent potential difference. Now think of the carrier as being controlled or modified by the code-signal; the result is a signal like that at the bottom of Fig. 15–5. The intervals of no radiation between dots and dashes can be considered as radiation of zero amplitude.

Figure 15–5 At the top is a high-frequency radio wave, called a carrier wave. Below it is the telegraphic code for the letter R (dot-dash-dot) converted to an electric signal. The bottom drawing shows the result of combining the two other waves. This may be thought of as a carrier frequency turned off and on by the audio signal.



The same general process can be used to impress any audio signal on a carrier wave. In Fig. 15–6, for example, the top wave form is a radio-frequency carrier. The second wave consists of a small portion of a voice signal. Figure 15–6c shows the result obtained when the amplitude of the carrier wave is modified, or **modulated**, by the audio signal. Remember that for broadcasting purposes the unmodulated carrier wave is of no value because it bears no signal, no ideas, no communication. The audio wave by itself is of no value since its frequency is so low that it will not radiate effectively. Only the modulated carrier wave is useful for radio communication. In this case the wave is called an **amplitude-modulated** carrier wave; the system is **amplitude modulation (AM)**.

15–12 The frequency of a carrier wave can be modulated. As the name suggests, **frequency modulation (FM)** communication systems accomplish modulation by varying the *frequency* rather than the *amplitude* of

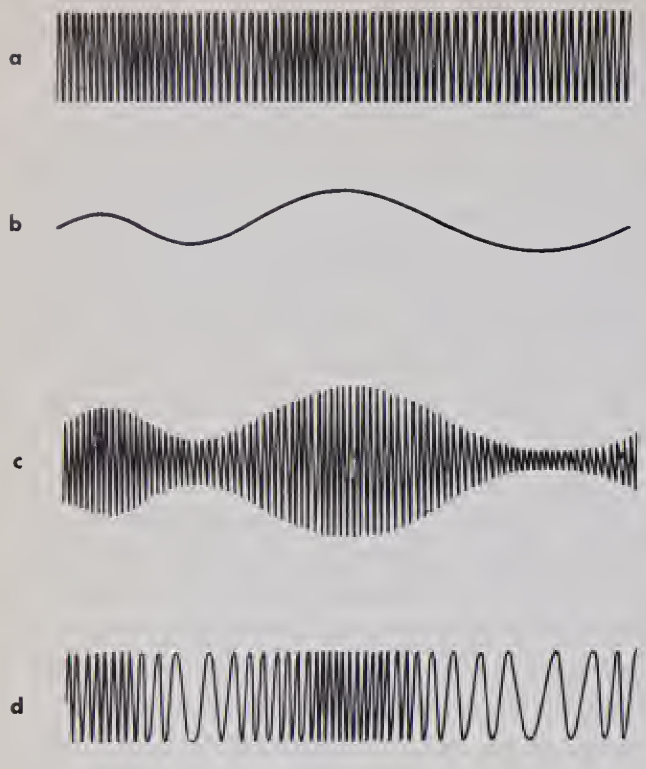


Figure 15–6 These wave forms illustrate the difference between amplitude modulation and frequency modulation. At the top is an unmodulated carrier wave. Below it is an audio signal. The third wave form is the .carrier, amplitude-modulated by the audio signal. The fourth wave form is the carrier, frequency-modulated by the same audio signal. Notice that the last wave shows variable frequency but constant amplitude.

the carrier wave. Such wave forms are illustrated by Fig. 15–6d.

As an illustration, assume that a carrier wave with a frequency of 100 Mc (100,000,000 cps) is to be modulated by an audio note of 400 cps. Under these circumstances, the frequency of the carrier will not be constant at 100,000,000 cps but will fluctuate above and below this value 400 times/sec. The greater the amplitude of the audio signal, the greater will be the magnitude of the fluctuation. For example, if the audio signal is of normal amplitude, the frequency of the modulated carrier may vary from 99,990,000 to 100,010,000 cps. If the signal is a louder one, the frequency might vary from 99,950,000 to 100,050,000 cps. The carrier frequency changes from one extreme to the other and back again at a rate determined by the frequency of the audio signal.

15–13 FM has many advantages over AM. FM radio communication has the following advantages over AM:

1. Less interference from most kinds of static. (Most static is amplitude modulation, and a good FM receiver is "deaf" to amplitude modulation.)
2. Less trouble due to "fading" of the signal.
3. Less overlapping of two stations close to each other on the dial.

In addition to these advantages, which are inherent in FM systems, other differences exist due to the frequencies which the Department of Transport has assigned to broadcast AM and broadcast FM. Remember, the former has a frequency range of from 0.54 to 1.6 mc, while the latter ranges from 88 to 108 mc, about 100 times as great a frequency. Because FM broadcasting is done at a higher frequency:

1. FM transmission can be more easily concentrated in one desired direction.
2. FM stations have less range than do AM stations because high frequencies do not follow the curvature of the earth. Instead they travel in straight lines. FM signals seldom can be received beyond 100 mi. As a result, many more station licenses can be issued, since it is very unlikely that two stations on the same wavelength and a few hundred miles apart will interfere with each other.
3. Tuned circuits in FM receivers offer more trouble from drifting of frequency due to changes in temperature. For this reason, some home FM

receivers must be retuned after they have warmed up.

For the critical listener, another outstanding difference between the two systems of modulation can be traced to DOT regulations. Because of the nature of AM systems, and because station licences are assigned at intervals of 10 kc, the DOT requires practically all broadcast AM transmitting stations to reduce sharply the amplitude of notes above 5 kc. This means that genuine high-fidelity reproduction of music or speech is impossible on the broadcast AM band. No such limitations are imposed on FM broadcasting.

Do It Now

Examine the tuning dial of an FM receiver and compare it with that of an AM receiver. How do the tuning ranges compare? If a good receiver is available, compare the fidelity of FM-reproduced music with that reproduced from AM signals. In particular note the presence of very high notes. Can you hear the difference? What other differences in quality of reception can you notice?

15–14 An oscillator and a modulator are basic parts of a transmitter. The electronic details of a modern radio transmitter are very complex. However, you are already familiar with most of the basic principles and some of the devices like microphones, amplifiers, and antennas. You can now investigate the production of the carrier frequency and the process of modulation.

Many kinds of circuits can be used to produce the high frequency necessary for a carrier wave; these are called **oscillator** circuits. The typical oscillator contains one or more resonant circuits (see p. 315), which determine the frequency of oscillation. A simple oscillator circuit is shown in Fig. 15–7. Notice the plate circuit: battery to cathode, to plate, and around through the resonant circuit (made of the capacitor and coil). Plate-current changes cause fluctuations in the resonant circuit. The capacitor can be adjusted for the desired resonant frequency. Because the coil of the resonant circuit is the primary of a transformer, similar fluctuations are induced in its secondary winding. The secondary is connected to the grid of the tube, giving the grid a fluctuating potential. This feedback to the grid is amplified by the tube and reinforces the fluctuations in the plate current at the natural frequency of the resonant circuit. If the oscillator is being used to produce audio-frequency oscillations, you can hear them by putting earphones in the plate circuit. With some modifications, such a circuit could be used to produce radio-frequency oscillations for a carrier wave.

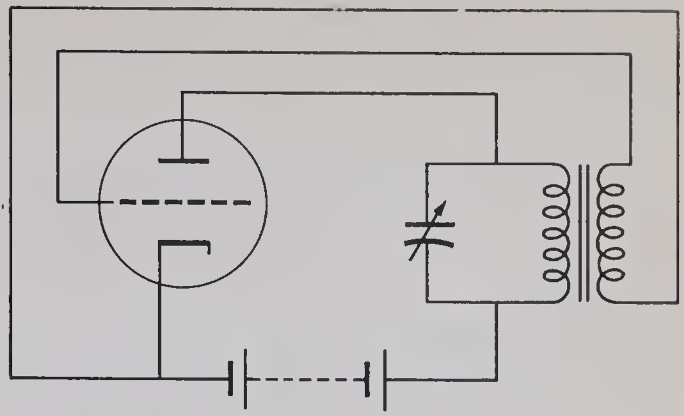


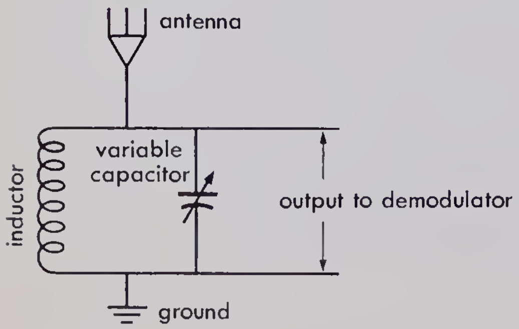
Figure 15–7 This is a simple oscillator circuit.

Suppose that a broadcasting station has been assigned a frequency of 1000 kc. Its oscillator has been designed to produce a current of that frequency. Next, the radio-frequency carrier must be modulated by the audio-frequency signal of the sound that is to be broadcast. This can be done in several ways, which are not discussed here because the methods are complicated. Finally, the signal-modulated carrier is sent to the broadcasting antenna.

15–15 Each carrier wave has a different frequency. From the antenna, the modulated carrier frequency radiates out into space as an electromagnetic wave. When it is intercepted by the antenna of a radio receiver, a tiny bit of the energy of the wave produces an alternating emf in the antenna.

With commercial, military, and amateur radio communication, there may be several hundred different carrier waves striking your receiving antenna at one time. All these signals exist simultaneously in the antenna circuit. How is it possible to select the one you want and reject all others? Selection is possible only because the carrier waves are at different frequencies. This is true because the Department of Transport assigns carrier frequencies to licensed transmitters. Of course, weak stations which are geographically very far apart can use the same transmitting frequency. Resonant circuits have the ability to select a single frequency or limited band of frequencies, as pointed out in Chapter 13. Thus a resonant circuit, as in Fig. 15–8, selects the carrier wave whose frequency corresponds to its own and rejects all others. The variable capacitor permits the user to select the carrier wave he wishes to receive.

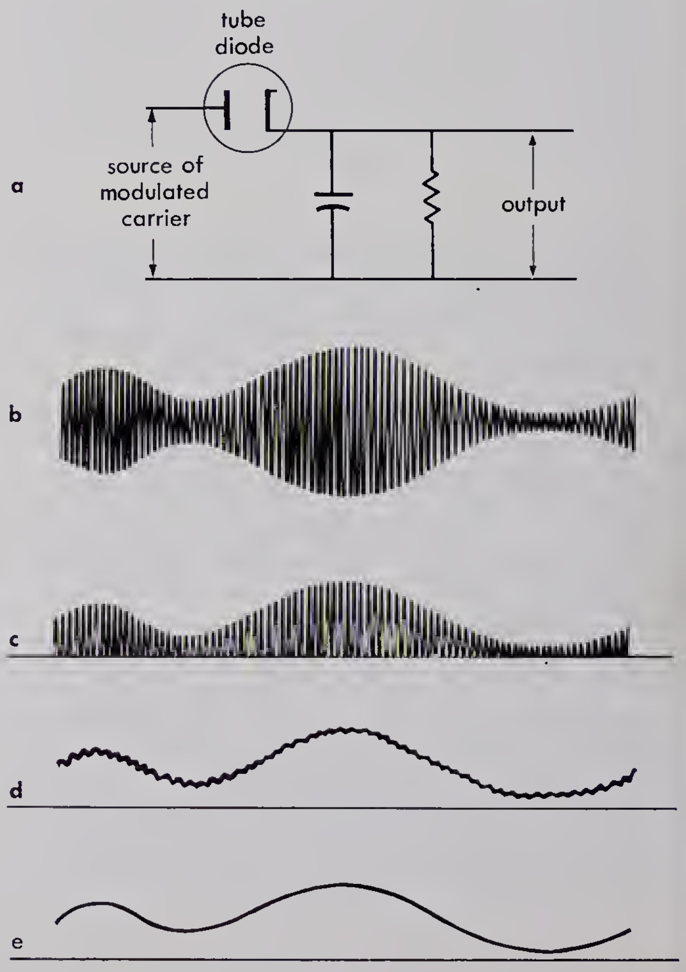
Figure 15–8 Here is a very simple circuit in a radio receiver. If built, it would work; but it would not be extremely selective unless additional resonant circuits were employed. If the output of this circuit is connected to the input of Fig. 15–9, and earphones used, it would be the modern equivalent of old-time crystal receivers.



15–16 Demodulation can be accomplished by a rectifier. Needless to say, a modulated carrier wave is completely inaudible; its frequency is far beyond the range of human hearing. Therefore, there must be some arrangement for separating the audio signal from the carrier frequency. This process is called **demodulation** or **detection**.

The general theory of demodulation is the reverse of modulation. The simplest circuit for accomplishing AM demodulation makes use of a half-wave rectifier. The operation of the circuit is much like that of the rectifier of Fig. 14–7 on p. 338. This

Figure 15–9 a. The circuit of a simple diode detector. **b.** The modulated carrier signal from the antenna circuit of Fig. 15–8. **c.** The signal after it has been rectified by the diode. **d.** The signal after it has been filtered by the capacitor. **e.** The wave form of the original audio signal. Note that the filtered signal in **d** is almost like that of **e.**



diode half-wave-rectifier circuit, commonly called a **diode detector,** is by far the most common in today's radio receivers.

The circuit of the diode demodulator is shown in Fig. 15–9. The input is the modulated carrier. At this stage it has already been picked up by the antenna; it is an electric signal. The diode (which may be a vacuum tube or a semiconductor crystal diode) rectifies this ac signal to give it the wave form of Fig. 15–9c. The rectified current exists in the resistor, which is literally the load for the circuit. A capacitor in parallel with the load resistor filters the rectified signal (see Fig. 15–9d for wave form). This is equivalent to the heavy wave form of Fig. 15–9e. This set of illustrations should be carefully compared with Fig. 14–7 and also with Fig. 15–6.

A summary of what happens in radio communication is given below.

Self Check

1. A 1-Mc carrier frequency is modulated by a 1000-cps audio note. How many times per second does the amplitude of the carrier frequency rise to a maximum value?
2. What is the nature of the received signal at a radio set during an interval between sentences when there is silence in the set's speaker?
3. What is the basic difference between FM and AM?
4. Why are FM transmission and reception freer of static than is AM communication?

RADIO COMMUNICATION — A SUMMARY

stated in common terms	*stated in technical terms*
1. Sound is converted to a pattern of variations of electric energy, called an audio signal. This audio signal is then amplified.	1. Sound energy is transduced to an audio signal and amplified.
2. Another electric signal is produced at frequencies far above the audio range. These are sine waves whose frequency is suitable for electromagnetic radiation.	2. A radio-frequency carrier is produced.
3. The audio signal is superimposed on the high-frequency sine wave signal.	3. The carrier is modulated by the audio signal.
4. The combination of audio signal and high-frequency sine waves is converted to electromagnetic radiation and is broadcast.	4. The modulated carrier is radiated from a transmitting antenna.
5. The electromagnetic radiation (consisting of audio signals superimposed on the high-frequency sine waves) is picked up by a receiving antenna and converted to electric current.	5. The radiated modulated carrier is converted to an electric current in the receiving antenna.
6. The audio signal is separated from the high-frequency sine waves with which it was combined.	6. The received signal is demodulated.
7. The audio signal is increased and converted to sound.	7. The audio signal is amplified and transduced to sound energy.

5. Broadcast AM music cannot reproduce the highest frequencies of the audio range. Why?
6. Why do not broadcast FM and AM signals have the same distance range, assuming both transmitters have the same power?
7. If a carrier frequency of 105.2 Mc is frequency-modulated with an audio note of 3000 cps, at what rate does the frequency of the carrier vary?
8. What kind of circuit is used in a transmitter to produce the carrier frequency?
9. In a radio receiver, how are undesired signals kept out of the antenna?
10. How does a simple diode demodulator circuit resemble a half-wave rectifier circuit?

Discussion Questions

1. In a frequency-modulated carrier, what is the difference between a weak signal of 500 cps and a strong signal of 500 cps?
2. In an FM carrier, what is the difference between two signals of equal amplitude, one of 500 cps, the other of 1000 cps?
3. In Fig. 15–9, what would be the practical result if the diode were reversed in polarity?
4. If it were practical to broadcast an electromagnetic wave at audio frequencies, how could it be separated at the receiving end from other such broadcast programs?

The Oscilloscope — A Basic Electronic Tool

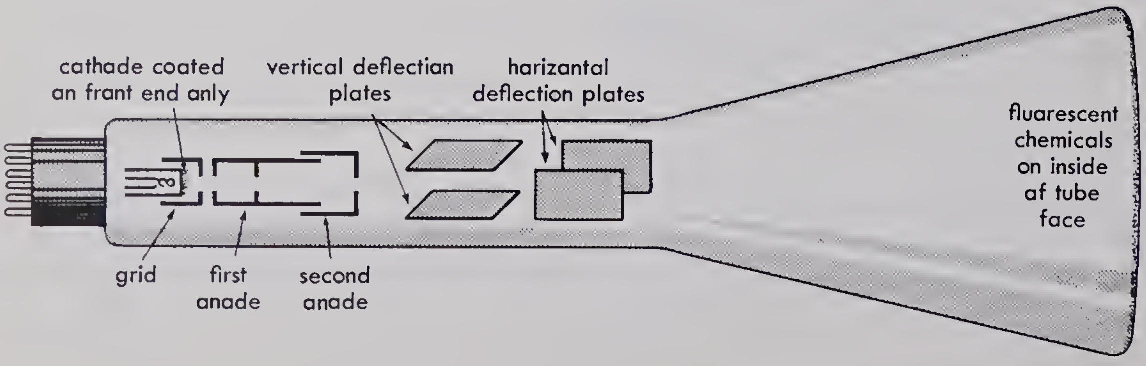
A look at some of the special applications of communications electronics rightfully starts with the oscilloscope. This is a basic tool for the modern electronics technician, regardless of the kind of work he does.

Most electrical measuring instruments involve some sort of meter movement. They usually indicate the magnitude of an electrical variable such as current, power, or frequency. An **oscilloscope**, however, is a different sort of test equipment. While it can be used to indicate the magnitude of potential difference, or indirectly many other variables, its chief function is to examine the wave-form of a signal, either ac or fluctuating dc.

15–17 An oscilloscope uses a special electron tube. The heart of an oscilloscope is a special electron tube known as a **cathode-ray tube**. It gets its name from its outstanding feature, a slender stream of electrons which comes from the cathode, and hence is called a **cathode ray**. The cathode-ray tube is shown in side view in Fig. 15–10. Here is how it functions:

1. A heated cathode emits electrons. The cathode is coated with oxide only at the end, and thus emits electrons primarily in that direction.
2. The grid is a hollow cylinder with a perforated disk inside it. The grid

Figure 15–10 This is a simplified diagram of a cathode-ray tube, as used in oscilloscopes. The inside of the tube is coated with a thin layer of carbon so that electrons which strike the tube face can leak back to the positive terminal of the power supply.


cathode coated on front end only
vertical deflection plates
horizontal deflection plates
fluorescent chemicals on inside of tube face
grid
first anode
second anode

partly surrounds the cathode. Like most grids, it operates at a potential which is negative with respect to the cathode. It is used to control the intensity of the electron beam.

3. The anodes (two are shown in Fig. 15–10) attract electrons and cause a stream of them to come through the hole in the grid. The anodes are cylinders, the second one more positive than the first. They draw a very small amount of current as electrons hit them, but their primary purpose is to accelerate the electrons and to focus the beam on a small spot on the face of the tube.

The total assembly of heater, cathode, control grid, and one or two focusing-and-accelerating anodes is frequently termed the **electron gun**. As the electrons leave this, they are in a narrow beam and move at high speed in a straight line. If there were nothing else in the tube, they would strike the end of the tube in the center and then leak along the inside surface of the tube back to the positive end of the power supply.

4. One end of the tube is coated with a phosphor which fluoresces when bombarded by electrons. The electron stream, of course, is completely invisible. However, when the electrons strike the chemically coated screen, they cause the phosphor to glow a green, white, or yellow color. Remember, it is not the electrons themselves which are visible; they merely impart their kinetic energy to the fluorescent screen, which releases it in the form of light energy. In most cathode-ray tubes, the coating continues to glow as long as the electrons are striking it, but ceases to glow a fraction of a second after the electron beam stops or moves elsewhere.

Do It Now

The first primitive cathode-ray tube was developed in the 1870's. Why do you suppose it came to be called a cathode-ray tube rather than an electron-beam tube?

15–18 Electric fields control the path of the electron beam. The path of the electron beam is controlled by the four deflection plates shown in Fig. 15–10. These are referred to as upper and lower, left and right, as seen from the front or screen end of the tube. **Deflection plates** cause the beam of electrons to bend away from their straight-line path. When any pair of plates, say the upper and lower, are at the same potential, they produce no effect on the beam. However, if the upper one is positive with respect to the lower, the beam of electrons is attracted upwards by the upper plate, and repelled upwards by the lower plate. As a result, the electron beam strikes the screen above center. The distance above center at which it strikes is determined by the magnitude of the potential difference between the deflection plates. If the polarity of this potential difference is reversed, then the beam is deflected downward instead of upward. In a similar way, potential difference between the left and right deflection plates can deflect the spot either to the left or right of the center. As a result, the electron beam can be made to strike anywhere on the surface of the screen by the proper combination of potential differences between the two pairs of deflection plates.

Note here that the two plates which are physically in a *horizontal* plane actually produce *vertical* deflection. On the other hand, the left and right deflection plates are in a *vertical* plane but produce *horizontal* deflection. Because their function is of greater interest than their physical position, the upper and lower plates are referred to as vertical deflection plates, and the left and right ones as horizontal deflection plates.

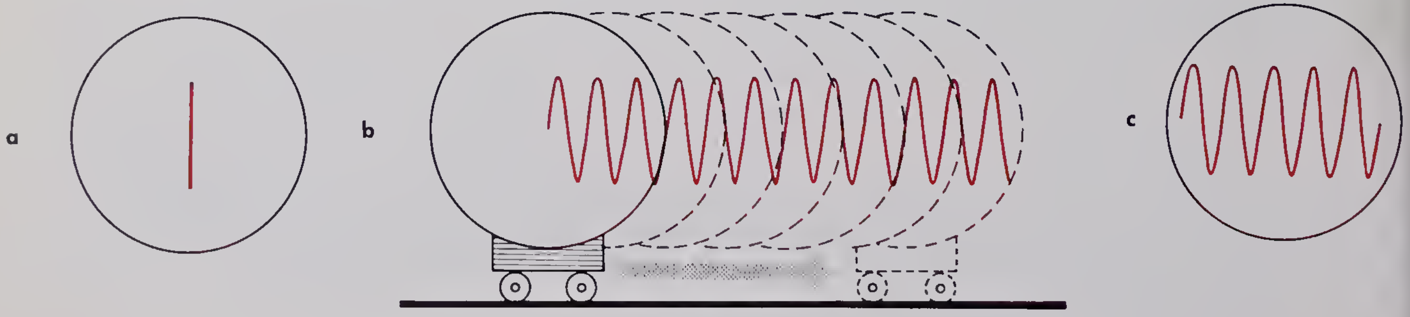
15–19 The electron beam can be controlled to trace a graph. How can a cathode-ray tube be used to trace graphs, to make wave forms visible? Assume that the signal to be examined is a fluctuating potential difference, and this is placed across the vertical deflection plates. Suppose that the signal is a 1000-cps sine wave. In this case, the spot would move merely up and down on the face of the tube, as shown in Fig. 15–11a. This, of course, would be of no value at all.

The way to make this vertical movement into a graph is to move it from one side to the other rapidly enough to "stretch out" the 1000-cps sine wave so that it can be distinguished. If the cathode-ray tube were placed on roller skates, and moved rapidly from left to right, as in Fig. 15–11b, then the electron beam would trace a sine wave across the room. This could actually be photographed by time-exposure photography. Although this arrangement is theoretically acceptable, it is certainly not practical.

In an oscilloscope this function is carried out electronically. A special signal is applied to the horizontal deflection plates to move the spot from left to right at uniform speed, then from left to right again, and again, and again, and again. The return of the spot from right to left is accomplished so quickly that it is unnoticeable. In a very real sense, it does not move "back and forth," it moves "forth and forth." Suppose now that the spot moves across the face of the tube in 1/200 sec. During this time, five complete cycles of the 1000-cps sine wave have been traced out by the spot, as in Fig. 15–11c. Then, if this process is repeated without delay, five more cycles will be traced. But since the second five are the same size and shape as the first five, the second trace coincides exactly with the first trace. As long as the 1000-cps sine wave remains unchanged, each successive left-to-right sweep of the spot will trace out five more identical sine wave cycles.

All this is taking place at the rate of 200 sweeps/sec. When a spot of light is moving that fast, it appears to be a complete and solid line to the eye. The eye continues to see a light for about 1/10 sec after it is gone, so if the spot retraces its path every 1/200 sec, the eye sees it as a steady image. Remember, whatever trace you see on an oscilloscope is not really a line, but always a rapidly moving spot.

Figure 15–11 If a 1000-cycle-sine potential difference were placed across the vertical deflection plates of a cathode-ray tube, the result would be a repeated vertical movement of the spot on the tube face, as shown in **a**. If the entire set-up were rapidly rolled from left to right, as suggested in **b**, a continuous sine wave would be sketched out by the moving spot. In **c** the spot is moved linearly from left to right in 1/200 sec. This traces out five complete cycles of the 1000-cycle sine wave signal. In the next left-to-right trip, the next five cycles are traced out and duplicate the first five.



Do It Now

If an oscilloscope is available, ask your instructor to help you put a 60-cps signal on the vertical deflection plates, and to adjust the frequency of the horizontal sweep. Can you produce two complete cycles of sine waves on the face of the instrument? one complete cycle? five complete cycles? Can you slow down the sweep enough to see that the line is really a moving spot?

Self Check

1. In what respect is an oscilloscope a different kind of test equipment than that represented by ammeters, voltmeters, etc.?
2. What is the origin of the light energy which is produced at the face end of a cathode-ray tube?
3. What would be the condition of the deflection plates, as seen from the front of the cathode-ray tube, to put the electron beam above and to the left of center?
4. Why is it that in a cathode-ray tube the horizontal deflection plates lie in a vertical plane, while the vertical deflection plates lie in a horizontal plane?
5. What is the function of the horizontal sweep circuit in an oscilloscope?
6. If a wave-form on the face of an oscilloscope repeats itself 75 times/sec, why does it not appear to flicker?
7. What would be the pattern on the face of an oscilloscope if a 6-kc sine wave is impressed on the vertical deflection system, while the horizontal sweep is at a frequency of 1500 cps?

Discussion Questions

1. Why are amplifiers needed in the horizontal and vertical circuits of an oscilloscope?
2. What would be the nature of the trace on the face of an oscilloscope if a dc potential difference were placed across its vertical input terminals?
3. Suppose there is something wrong with an oscilloscope circuit, and although the vertical deflection plates and the signal feeding them are normal, the right deflection plate is somehow connected directly to the upper deflection plate, and the left deflection plate is similarly connected to the lower deflection plate and neither is connected to the horizontal sweep. What kind of trace would appear on the tube face when a vertical signal is applied to the proper input terminals?

Television and Telemetering

15–20 A television camera employs photoelectric emission. Television camera tubes are of different types. One of the first successfully used was called the **iconoscope**. Most modern TV cameras use a much more sensitive tube known as the **image orthicon**. However it is extremely complicated, and a thorough study of its operation would serve no purpose here.

You already know that if sufficient energy is available, electrons are emitted from the surface of conductors. At the hot cathodes of vacuum tubes, this energy is supplied by heat, and thermionic emission results. It is also possible to release these electrons by providing light energy to overcome the work-function (p. 335) of the emitting surface; this is **photoelectric emission**. The devices which provide photoemission are called **photoelectric cells**.

The heart of the iconoscope is a flat surface made up of millions of tiny globules of light-sensitive material; this screen is commonly referred to as a **mosaic screen**.

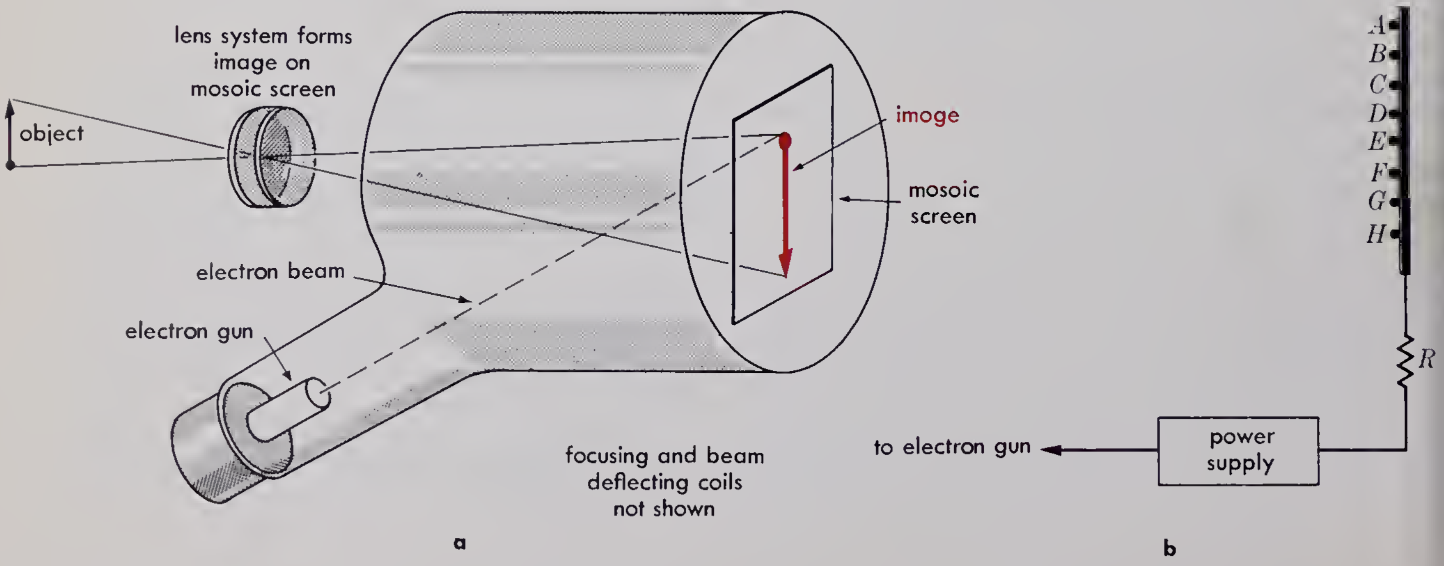
Figure 15–12a shows a diagram of an iconoscope tube. The tube contains an electron gun and deflection coils. The mosaic screen is placed so that an optical image can be focused on it by a converging lens, as in a camera. It is also in such a position that it is struck by the electron beam from the electron gun.

A simplified diagram of a bit of the mosaic screen is shown in Fig. 15–12b Here only eight of these tiny light-sensitive globules are shown. These facts will help you understand the operation of this screen:

1. Each globule is insulated from the others.
2. The globules are exposed to varying intensities of light (from the lens.)
3. The globules exposed to the most light emit the most electrons, and therefore become more positive than those exposed to little or no light. The emitted electrons leak along the inside surface of the tube and then back to the positive end of the power supply.
4. The globules are located close to but not touching a conducting sheet. Thus, each globule forms one plate of a capacitor. The conducting sheet serves as the other plate for all the photoelectric cells. The metal sheet is connected to the power supply through a high-resistance path, *R*.

15–21 The optical image is transduced to an electric (video) signal. What is the condition of this mosaic screen of photoelectric cells after the lens has focused an image on it for a fraction of a second? Each globule has emitted some electrons, and is therefore positive to some degree. The magnitude of the charge depends on the intensity of light which shines upon that particular globule. For simplicity, assume that in Fig. 15–12b globule *A* is in a very bright part of the image, globule *C* in a gray part, and globule *F* in a very dark part. As a result, globule *A* will be highly positive, globule *C* somewhat positive, and globule *F* barely positive. But the average charge on the screen is definitely positive. By induction, the metal sheet immediately

Figure 15–12 These are highly simplified diagrams of an iconoscope, a simple type of television camera tube. **a.** This shows the relationship between the lens, the mosaic screen, and the electron gun, which provides the beam of electrons to scan the mosaic screen. **b.** Here is an idealized diagram of eight of the millions of globular photoelectric cells on the mosaic screen. Note that each cell acts as one plate of a tiny capacitor. The heavy plate behind them acts as the other plate for all the capacitors.



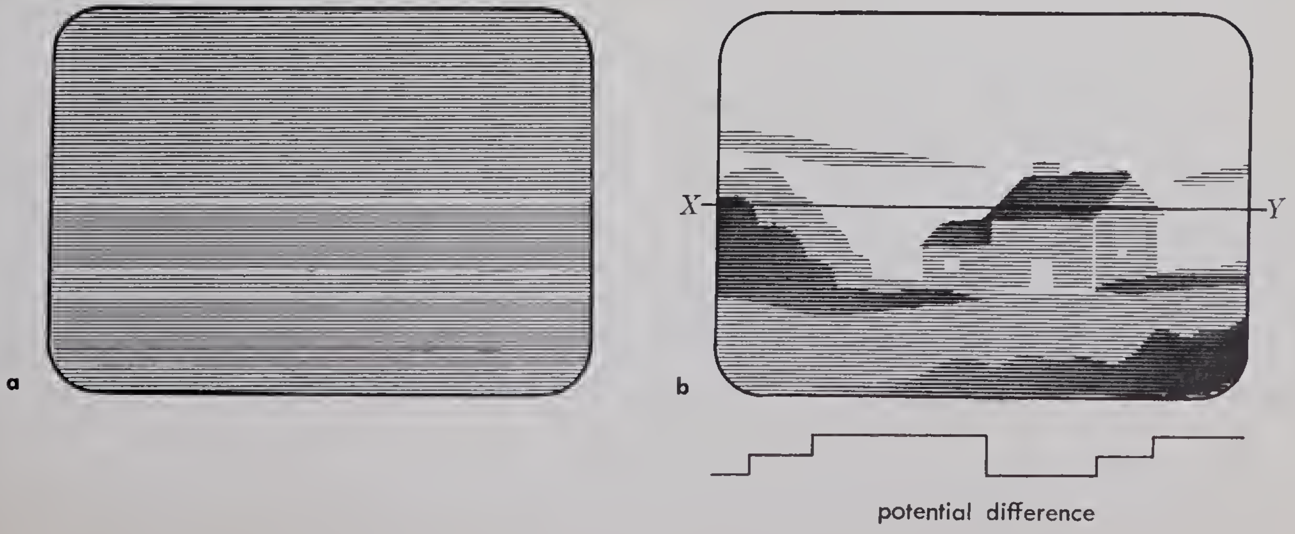
behind it therefore becomes negative; that is, it acquires electrons through the resistor, *R*.

The deflection coils of the iconoscope are provided with currents which cause the electron beam to sweep over the entire mosaic screen 30 times each second. Modern television accomplishes this complete scanning pattern by making 525 horizontal paths over the screen each 1/30th sec. The scanning pattern for a single frame accomplished in 1/30th sec is something like that in Fig. 15–13a.

Referring back to Fig. 15–12b, what happens when the electron beam strikes globule *A*? Globule *A* is highly positive, but the electron beam replenishes the electrons and makes it less positive. This reduces the average positive charge of the entire mosaic screen slightly. As the mosaic screen becomes less positive, it has less attraction for the free electrons in the nearby sheet, so the sheet loses some of its negative charge. It can do this only by permitting some electrons to flow down through the resistor *R* to the power supply. Thus the result of the electron beam scanning over globule *A* is a spurt of electrons down through *R*. When the electron beam scans globule *C*, the same thing happens, only to a lesser degree, since globule *C* has a less pronounced positive charge. When the beam scans globule *F*, the corresponding flow of electrons through *R* is very slight indeed.

For sake of illustration, suppose that in the process of scanning, the electron beam covers a path corresponding to the line *X*-*Y* in Fig. 15–13b. Moving from left to right, the beam first encounters cells that are in weak light, then in moderate light, then in strong light, again in weak light (the shaded roof), again in moderate light, and then again in an area whose globules were strongly illuminated by the sky. The beam therefore produces a weak, then a moderate, a strong, a weak, a moderate, and finally another strong flow of electrons down through *R* in Fig. 15–12b. The resulting potential difference across *R* is as indicated in the bottom graph of Fig. 15–13b. In this way, the pattern of dim, intermediate, and bright light which the camera lens has cast upon the mosaic screen is transduced into an electric signal which corresponds to an image. This is called a *video* signal. It is amplified and used for AM modulation of a carrier, and it is broadcast in the form of electromagnetic radiation.

Figure 15–13 **a.** This is the general nature of the scanning pattern, or "raster," of modern television. There are 525 lines in each complete frame, and there are 30 frames per second. The 525 lines are scanned in two sections, first the odd-numbered lines, then the even-numbered lines. This interlaced scanning pattern reduces flicker and eye fatigue. **b.** This diagram shows how a single line can produce a segment of video signal when crossing a very simple scene. The video signal is shown below the diagram.



The *audio* signal is used for frequency modulation of a different carrier. The carriers for the two signals are so close in frequency that they are transmitted by the same antenna and received by the same resonant circuits in the TV receiver.

15–22 The video signal is transduced to a light-intensity pattern. The heart of a television receiver is a cathode-ray tube, commonly called a picture tube. This unit is almost exactly like the one used in the oscilloscope, except that it is usually larger, and glows bluish-white instead of green when struck by an electron beam. The modulated carrier wave is received by a sensitive receiver. After demodulation, the video signal is fed to the control grid of the picture tube, where it controls the intensity of the electron beam and hence the brightness of the spot of light on the screen.

The deflection coils cause the beam to move across the picture-tube screen with the scanning pattern of Fig. 15–13. Although these sweep currents are generated at the receiver itself, they are kept in step with those at the transmitter by a series of synchronizing pulses which are transmitted along with the video signal.

The video signal corresponds to the pattern of light intensities which the iconoscope electron beam scans. This video signal controls the intensity of the spot of light produced by the electron beam in the receiver picture tube. As a result, every area of light intensity in the iconoscope is reproduced as an area of corresponding light intensity on the TV screen.

15–23 Telemetering requires special transducers. It is often desirable to collect data from places where human beings should not or cannot go, such as within a highly radioactive region, or somewhere in outer space. The use of electric or radiated energy to transmit measurement data from remote locations is called **telemetering**.

One of the basic problems of telemetering is the design of a suitable transducer to convert the variable being measured to an electric signal. Sounds can be transduced with microphones; light intensity, with photoelectric cells. A temperature-sensitive resistor can be used to sense the intensity of heat, and G-M counters and other radiation detectors determine conditions of radioactivity. Almost any physical variable can be telemetered if someone is clever enough to invent a suitable transducer for it.

15–24 Space research makes wide use of telemetering. You can get a feeling for telemetering if you imagine that you are designing a system for measuring several variables at some remote location in outer space. Suppose you are working on a project whose objective is placing an artificial satellite in an orbit inside that of Mercury's. Other teams are working on problems of propulsion, timing of the launch, optical and radar tracking, and other aspects of the enterprise. Your task is to design a telemetering system to send back strategic data about physical conditions some 20,000,000 miles from the sun.

To make the sample problem simple, assume that only six kinds of information are needed. On the next page, in greatly simplified form, are possible ways of transducing each measurement to an electric signal.

Now how will all six measurements be telemetered at once? It is much easier to transmit the six signals one at a time. Therefore, you can install an automatic switch which picks up each signal in turn for 1 sec and uses it to modulate a carrier. Thus, each measurement is broadcast once in 6 sec, or 10 times/min. Of course, all this will be constructed in miniature to make it light, small, rugged, and economical of power. Since the unit is so close to the sun, it may even be practical to get the necessary power from solar cells.

TRANSDUCING PHYSICAL MEASUREMENTS

Physical variable	*Transducer*
1. Temperature within the artificial planet	A temperature-sensitive resistor is part of an electronic oscillator circuit. The frequency of the oscillator (perhaps a few thousand cycles per second) varies in a predictable way with the resistance of the resistor.
2. Occurrence of micrometeors (extremely tiny particles of solid material scattered throughout the solar system)	A strip of glass is coated with a thin layer of conducting material, so thin as to have an appreciable amount of resistance. As the space probe is struck by micrometeors, they erode the conducting layer and increase its resistance. The resistance is part of an electronic oscillator circuit, possibly the same one used above. The frequency of the oscillator thus depends on the cumulative eroding effect of micrometeors.
3. Visible-light intensity	A photoemission cell is equipped with optical filters which exclude all but visible light radiation. The cell charges a capacitor which is periodically discharged. The greater the light intensity, the greater is the pulse of current during discharge.
4. Ultraviolet-light intensity	The same type of circuit is used as for visible light intensity, except that optical filters are selected to admit desired ultraviolet radiation and exclude all others.
5. Gamma radiation	A G-M counter produces electric impulses whose abundance depends on the radiation intensity.
6. Magnetic flux density	A tiny loop of wire is continuously rotated. The strength of the generated emf depends on the magnetic flux density in the region of the coil.

Self Check

1. In an iconoscope tube, how do the globules on the mosaic screen acquire their electric charge?
2. How are the charged globules discharged?
3. In an iconoscope tube, how is the change of charge on the mosaic screen globules converted into an electric signal?
4. What type of modulation is used for the video signal and for the audio signal in television?
5. How long does it take the electron beam to sweep from left to right across a television picture once?
6. Why is it necessary to transduce data into an electric signal before it is telemetered?
7. What is the advantage of telemetering a set of data in sequence rather than simultaneously?
8. What is the basic difference between telemetering and a telephoned verbal report of the data?

Discussion Questions

1. Why must the photosensitive globules in an iconoscope's mosaic screen be insulated from each other?
2. Examine the picture on the face of a TV receiver. Can you see the lines? Try to count them. Do you find approximately 525 lines? (Some are hidden beyond the top and bottom of the screen.)
3. Closely examine a small section of the picture on a TV receiver. Can you see that each line varies in intensity from one side of the screen to the other? Do the lines also appear to vary in width?
4. The gasoline gauge in an automobile is at some distance from the fuel tank itself. This can be thought of as telemetering. Can you think of other examples in cars, at home, or in public buildings?

Chapter Summary

Electronic amplifiers operate from electric signals. Accordingly, signals must be converted from sound and other forms into electric form, and then from electric form to other energy forms. Devices which accomplish this are transducers. Some transducers operate on the principle of the motor effect or the generator effect, some are piezoelectric in character, and there are many other types. Without the many kinds of transducers, radio communication would be impossible.

The electric fields and magnetic fields produced by vibrating electric charges fluctuate in the same pattern as do the electric charges. These two fields constitute an electromagnetic wave in which the electric field, the magnetic field, and the direction of wave travel are mutually perpendicular. The electromagnetic wave travels through a vacuum at approximately 3×10^8 m/sec, and through air at slightly lower speed. Electromagnetic waves induce corresponding emf and current fluctuations in conductors which lie in their path. Radio waves are useful only at high frequencies, usually above 100 kc. For radio waves as well as for other kinds of waves, $v = f\lambda$. Audio signals are combined with radio wave frequencies by modulation of the carrier by the signal. The most common form of modulation is amplitude modulation (AM).

A carrier can be modulated by changing the carrier's frequency. This is called frequency modulation (FM). FM has several advantages over AM, due in part to the nature of the system, and in part to the restrictions established by the Department of Transport.

A radio-frequency carrier is produced by an electronic oscillator circuit, then modulated by an audio signal, and broadcast. Resonant circuits make it possible for a receiver to accept desired signals and reject undesired ones. Rectifier circuits provide one way of separating or demodulating an audio signal from the carrier frequency which it has modulated.

An oscilloscope is useful in examining waveforms in electric circuits. The oscilloscope uses a special type of electron tube, the cathode-ray tube, to trace out a graph of variations of potential difference with time. The beam of electrons in the tube is focused by controlled electric fields, and deflected by electric fields between two horizontal and two vertical deflection plates. The pattern on the face of an oscilloscope appears to be one or more lines, but is really a rapidly moving spot of light produced by the electron beam. The complete oscilloscope contains a horizontal sweep oscillator, amplifiers, power supplies, and other related circuits.

In one type of television camera, an optical image is projected on a mosaic screen of tiny photoelectric cells, thus giving them a pattern of charge. A moving electron beam discharges these in sequence, and thus transduces the pattern of light brilliance into a pattern of varying electric current. This is then used to modulate the amplitude of a carrier frequency, while the audio signal is used to modulate the frequency of another nearby carrier. At the receiver, the video signal is demodulated, amplified, and used to control the intensity of light at the face of the picture tube, whose sweep circuits are synchronized with those at the TV studio.

Telemetering is the automatic transmission of data through electric or radio circuits over substantial distances. This system is widely used in modern science, particularly that related to nuclear reactions and space research.

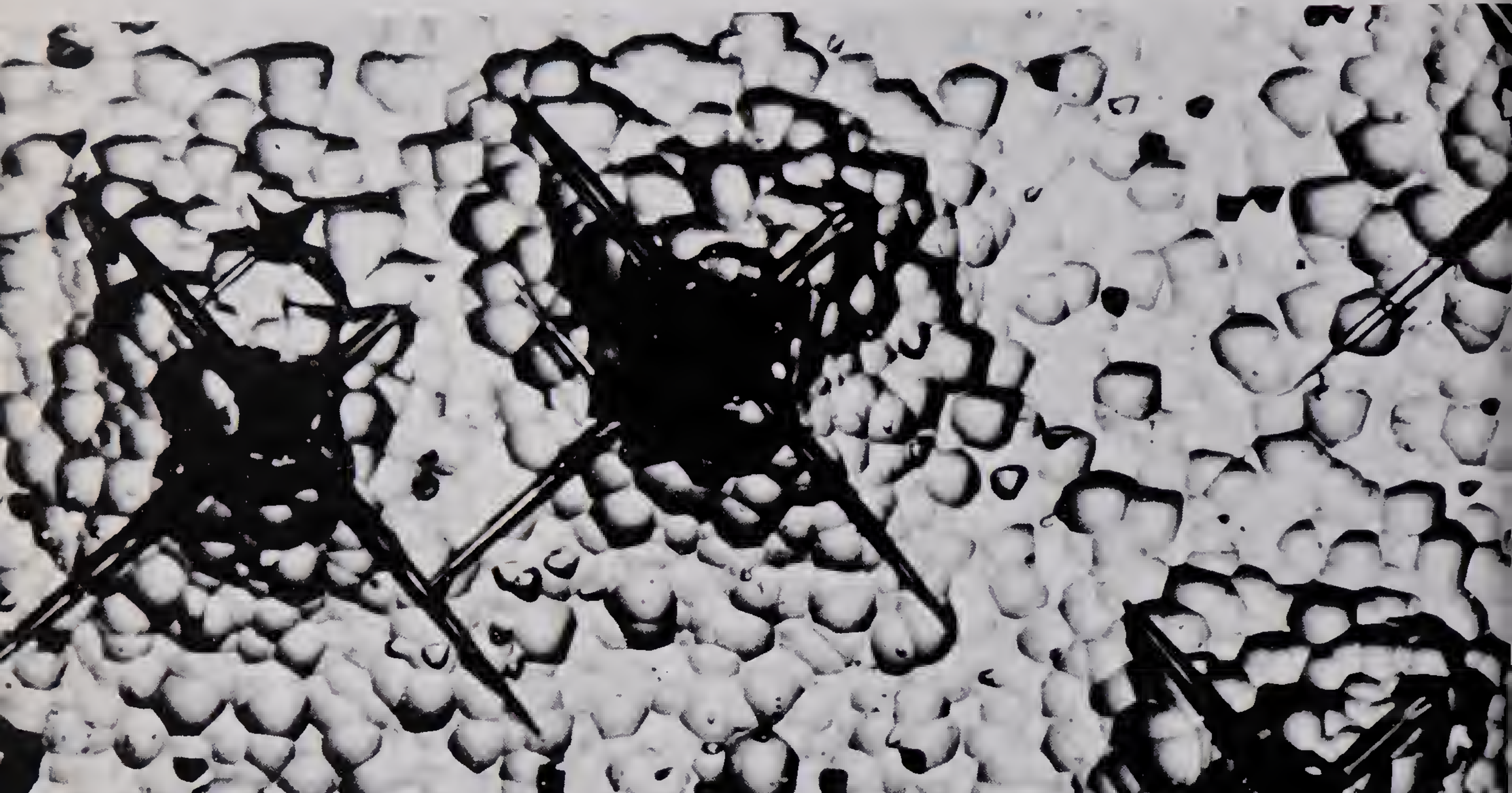
Vocabulary

transduce, transducer (*p. 353–355*)
phonograph pickup (*p. 354*)
microphone (*p. 354*)
speaker, dynamic speaker (*p. 354*)
voice coil (*p. 354*)
piezoelectric effect (*p. 355*)
crystal microphone (*p. 355*)
video signal (*p. 355, 368–369*)
radio waves (*p. 356*)
electromagnetic wave (*p. 356–358*)
kilocycle (kc) (*p. 357*)
megacycle (Mc) (*p. 357*)
audio frequency; radio frequency (*p. 358*)
carrier wave, carrier frequency (*p. 359*)
modulate, modulation (*p. 360*)
amplitude modulation (AM) (*p. 359*)
frequency modulation (FM) (*p. 359*)
oscillator (*p. 361*)
demodulation (detection) (*p. 362*)
diode detector (*p. 362–363*)
oscilloscope (*p. 364*)
cathode ray (*p. 364*)
cathode-ray tube (*p. 364*)
electron gun (*p. 365*)
deflection plates (*p. 364–365*)
horizontal sweep (*p. 366*)
photoelectric emission (*p. 367*)
iconoscope (*p. 367*)
image orthicon (*p. 367*)
photoelectric cell (*p. 367*)
mosaic screen (*p. 368–369*)
scanning (*p. 369*)
telemetering (*p. 370*)

Discussion Questions

1. Some people think that the energy produced by a dynamic speaker comes in part from the field. Explain why this idea is incorrect.
2. What evidence do you have that radio waves do not need air for their transmission?
3. What happens to the energy of a transmitted radio signal which is not picked up by receiving antennas in the vicinity?
4. In what sense are transmitting antennas and receiving antennas transducers?
5. What happens in a cathode-ray tube circuit when the intensity control is adjusted to make the spot on the face of the tube get brighter?
6. A 400-cps sine wave is applied to the vertical input terminals of an oscilloscope. The horizontal sweep signal is adjusted to 800 cps. What kind of trace appears on the face of the instrument?
7. What is the source of energy which releases electrons from the globules of the mosaic screen of an iconoscope tube?

CHAPTER 16



Courtesy of Bell Telephone Laboratories. From p. 141, TRANSISTOR TECHNOLOGY, Vol. III, edited by F. J. Biondi. Copyright 1958, D. Van Nostrand, Inc.

Four-pointed etch pits in a crystal of germanium. During the processing of germanium in the production of transistors, the outer crystals may be damaged; the surface of the germanium is therefore treated by a liquid that dissolves the damaged area.

Particles, Accelerators, and Holes

Thomson, Millikan, Shockley — these are the names of three important physicists and Nobel Prize winners.

Sir J. J. Thomson, an Englishman, carried on a brilliant series of experiments with electric currents in highly rarefied gases. He clearly established that the current in these gases consists of a flow of charged particles. This work led to his discovery of the electron.

Robert A. Millikan, an American, spent many years perfecting and carrying out an ingenious method for determining the charge of the electron. His research also included investigations of photoelectricity.

William Shockley, an American, directed a team of research physicists investigating the characteristics of certain metals in their solid state. An observation of some unusual behavior in the surface layers of the element germanium led to the development in 1948 of the transistor, the tiny electronic device which is now replacing vacuum tubes in many applications.

Each of these scientists received the Nobel Prize in Physics to honor his efforts. Their research was aimed at understanding the nature and behavior of matter, one of the great frontiers in modern physics. Accordingly, their work is involved in this chapter in which you will find out how scientists learned about electrons, how subatomic particles are accelerated to enormous speeds, and what is being learned through solid-state physics.

The Discovery of the Electron

16–1 Early experimenters used gas-discharge tubes. In Chapter 14 you studied electric current in tubes filled with gas at very low pressure. The performance of these gas-discharge tubes was explained in terms of the movements of negative and positive ions. This is the modern view and is consistent with what you know about the structure and behavior of matter.

But when these experiments were first performed, nobody had any inkling of the existence of electrons. The general nature

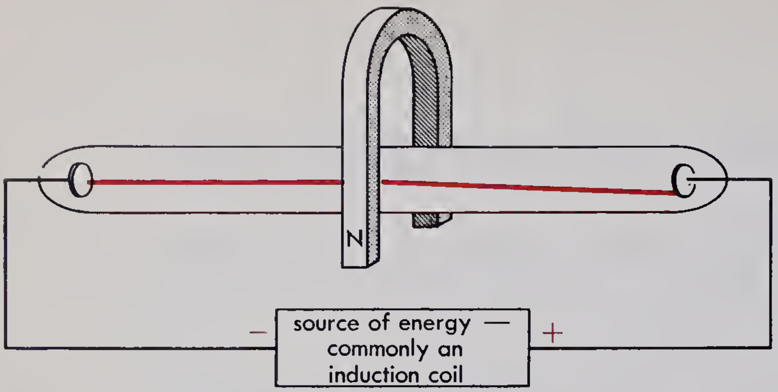


Figure 16–1 This experiment in a highly evacuated tube shows one of the early observations about this phenomenon. Here a *horizontal* magnetic field is producing a *vertical* deflection of the discharge beam.

of gas discharge was described as long ago as 1785. Other related observations were reported during the next seventy years. But these early experimenters were hampered by poor equipment. What was needed was an improved vacuum pump and a man superbly skillful in glass blowing.

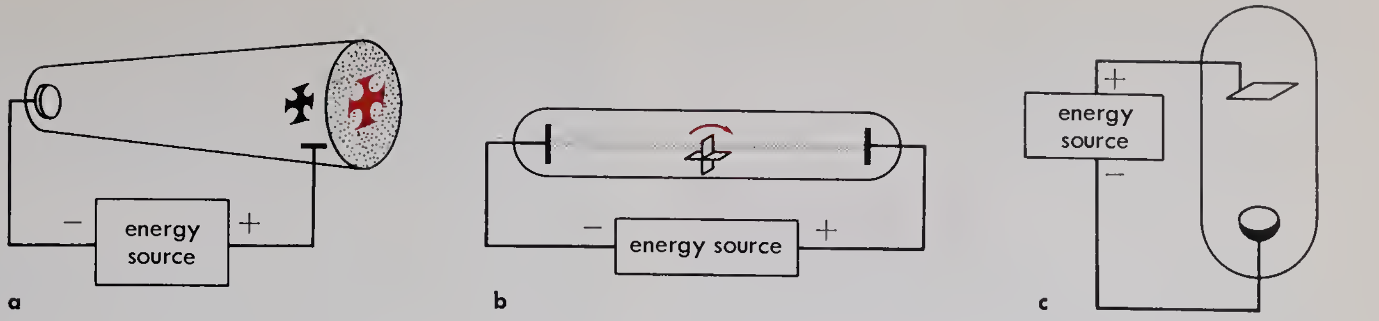
Therefore it was no accident that some of the early investigations of cathode rays were made by scientists in Bonn, Germany. For in Bonn lived Heinrich Geissler, not only an excellent glassblower but also the inventor, in 1855, of the first major improvement in vacuum pumps in over 200 years. With Geissler's invention and the tubes he was able to make from glass, scientists began an intensive study of the mysterious and exciting glow to be found in low-pressure gases and evacuated tubes. This illustrates the historical fact that major breakthroughs in science often must await advances in technology.

It was soon evident that cathode rays are affected by a magnetic field, as shown in Fig. 16–1. When it was suggested that cathode rays might consist of charged particles in motion, eager experimenters tried to deflect these charges by an electric field. All such attempts failed for many years, and the mystery of the real nature of cathode rays remained unsolved.

During this time some scientists felt that gas-discharge experimentation was being overdone. As often happens, research with cathode rays was ridiculed as being of no value. An industrialist who had financed a physics laboratory was invited in to see the spectacular gas-discharge phenomena his contributions had made possible. His comment on seeing it was, "How beautiful — and how useless!"

Much of the evidence about cathode rays indicated that they were negatively charged particles. However, no one was able to show that they could be deflected by an electric field. This situation caused many physicists to believe that they were electromagnetic waves, a sort of "invisible light." A series of experiments, including those suggested in Fig. 16–2 (largely the work of Crookes), showed that cathode rays travel in straight lines and that they have kinetic energy — or at least can produce heat. However, when it was found that cathode rays could penetrate thin layers of solids including metals, this was felt by some to be conclusive proof that the discharge could not possibly consist of charged particles.

One hypothesis was that the gas discharge was a kind of wave motion. Scientists at that time were just beginning to understand electromagnetic waves. During that period Maxwell developed the mathematical formulas to represent an electromagnetic wave, and Hertz demonstrated the existence of radio waves. It was nearly the dawn of the 20th century before there was good evidence that a gas discharge consists of moving charged particles.



Here , the metal ✠ inside the tube seems to cast a shadow on the tube's end. The glow on the end of the tube is a fluorescent effect due to minerals in the glass.

In this case , it appears that the discharge ray has kinetic energy, for it is able to turn the paddlewheel clockwise. It can be shown, however, that this *could* be the heating effect of electromagnetic (heat) waves.

The discharge ray made a red–hot spot on the positive electrode. This is further evidence that the discharge ray has great energy.

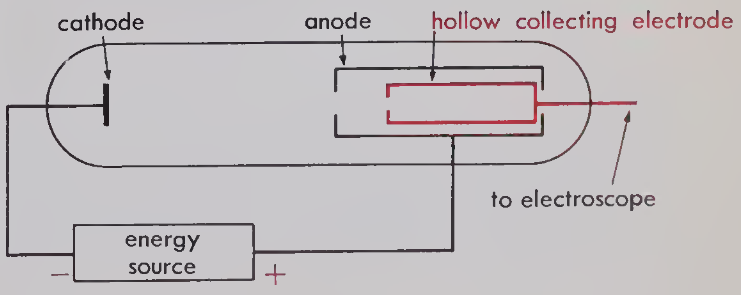
Figure 16–2 These early experiments helped pioneer scientists to learn about the nature of the rays in evacuated tubes. They seem to confirm the early conclusion that cathode rays consist of *something* going from the negative to the positive electrode.

16–2 Perrin determines the charge of the cathode ray. In 1895 Perrin of France performed an experiment which demonstrated beyond doubt that cathode rays consist of negative charges. He used a low-pressure gas-discharge tube with a hollow anode, as shown in Fig. 16–3. Most of the cathode rays struck the anode, but a small portion of the discharge went through the hole and accumulated on the inside of the hollow electrode. This electrode was connected to an electroscope and shown to have acquired a negative charge. However, a magnetic field would deflect the ray, so that although it penetrated the hole in the anode, it did not get into the hollow collecting electrode. When the ray was deflected, the hollow electrode collected no charge.

Today this seems like a simple experiment indeed. But when it was first done, the problems of getting high vacuum, high potential difference, and delicate instruments were much greater than they are now. Most important of all — then as now — it requires a brilliant mind to think of a new experiment such as this, and great resourcefulness to carry it out.

16–3 Thomson investigates the mass and charge of cathode-ray particles. J. J. Thomson went even farther than Perrin. Using a higher vacuum and other refined techniques, Thomson succeeded in deflecting a cathode ray by passing it between two oppositely charged metal plates. Because the ray consists of negative particles, it was attracted toward the positive deflection plate and away from the negative one. The

Figure 16–3 In Perrin's experiment the discharge from the cathode went toward the anode. A small part of the discharge entered the hole in the hollow collecting electrode. The electroscope, connected to the collecting electrode, indicated that a negative charge had been collected. When a magnet deflected the ray so that it still hit the positive electrode but not the hole in it, the collecting electrode collected no charge at all.



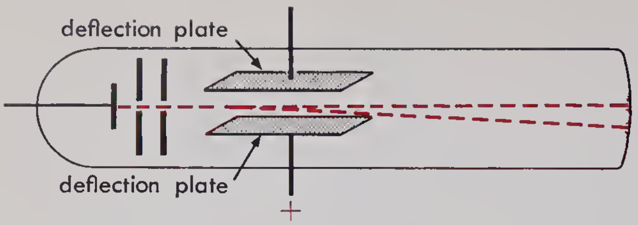


Figure 16–4 This diagram shows the type of discharge tube Thomson used for some of his early experiments. The cathode at the left gives off particles, which make up a sharp, well-defined beam as they pass through the two slits. The beam is then deflected as it goes through the electric field between the two deflection plates. The lower dashed line indicates the position of the beam when there is a field.

influence of a magnetic field on the cathode ray was also consistent with the hypothesis that it consisted of negatively charged particles. The big question now was, "What are these negatively charged particles?"

To tackle this problem, Thomson used apparatus similar to that of Fig. 16–4. The electric field between the plates produced a deflection of the electron stream, and hence of the bright spot which it produced on the end of the tube. From what you know about mechanical and electric forces, you can see that the deflection is greater when:

1. The electric field is greater;
2. The charge of the particle is greater;
3. The length of the plates between which the stream travels is greater.

Also, the deflection is less when:

1. The mass of the particles (and hence their inertia) is greater;
2. The velocity of the particles is greater, resulting in a smaller interval in which they are between the plates.

Three of the quantities involved — the deflection, the intensity of the magnetic field, and the intensity of the electric field — were easily measured. But the other three — the mass, the charge, and the velocity of the particles — were not easily measurable. However, Thomson developed an ingenious way of measuring the velocity of the particles. His method is based on the combined effects of electric fields and magnetic fields on moving charges. This is how he did it:

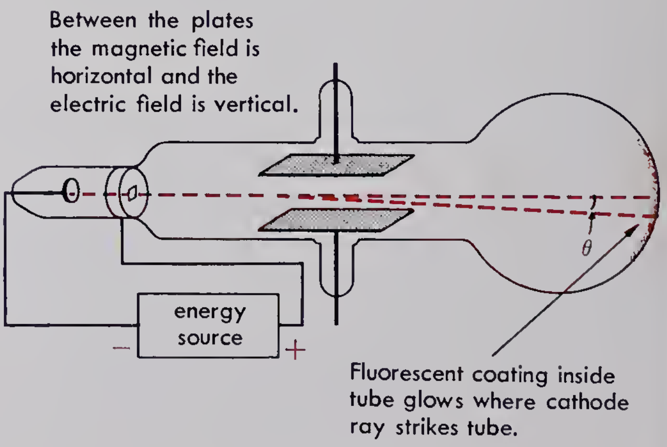
A cathode-ray tube can be set up as in Fig. 16–5 so that the ray can be deflected not only by an electric field, but also by a magnetic field. Either field can bend the beam of charged particles up or down depending on the direction of the field. The amount of bending depends on the strength of the field. The bending is due to a force acting on the negative charge while it passes between the plates. Thomson knew that the force F on a charge Q in an electric field E is

$$F = EQ \quad \text{(See Chapter 10)}$$

He also knew that a charge Q moving at velocity v across a magnetic field B experiences a force F.

$$F = BvQ \quad \text{(See Chapter 12)}$$

Figure 16–5 With apparatus similar to this Thomson noted that the cathode ray was bent through the angle θ by the electric field between the plates when there was no magnetic field. Then he adjusted and recorded the field strengths until θ became zero. From the data he calculated the velocity of the particles. From the value of θ he calculated m/e, the ratio of the mass of a particle to its charge.


Between the plates the magnetic field is horizontal and the electric field is vertical.
θ
energy source
−
+
Fluorescent coating inside tube glows where cathode ray strikes tube.

The electric field and the magnetic field in Fig. 16–5 can be adjusted so that the forces they produce are equal and opposite — so there is no deflection at all. Under these conditions the two forces are equal, so

$$EQ = BvQ$$

Then

$$v = E/B$$

Since both E and B are readily measured, Thomson could solve for v, the velocity of moving charges. The figure he arrived at was roughly 3×10^7 m/sec — an amazingly high velocity — about 1/10 the speed of light.

Thomson now knew the velocity of the particles, but still did not know their mass or charge. By using the same tube, with an electric field only, he was able to measure the deflection of the ray, and from this to obtain the ratio between the mass and the charge. Since the mathematics is complex, Thomson's derivation is not given here. He calculated the ratio of mass to charge of the cathode-ray particle as about 10^{-11} kg/C. Now at this time the smallest known particle was the hydrogen atom (actually an ion), for which the corresponding ratio was about 1000 times greater. The clear indication was that either the mass of the cathode-ray particle was extremely small, or its charge was extremely large.

Thomson developed an intricate scheme for determining the charge of the electron, although his results were neither consistent nor reliable. However, they clearly indicated that the charge of this new particle was approximately the same as that of the hydrogen ion. From this it followed that the mass of the new particle was vastly smaller than that of the hydrogen atom. Perhaps atoms were not the smallest building block of matter after all.

Thomson called the new particle the *electron*, a name which had been suggested some time before. For this work he was knighted and in 1906 was awarded the Nobel Prize in Physics.

Self Check

1. In what way was thorough research into electric currents in low-pressure gases dependent on technological developments?
2. How does the fact that cathode rays are deflected as they move across a magnetic field suggest that they are charged particles in motion?
3. How does the sketch in Fig. 16–1 suggest that cathode rays are negative particles rather than positive particles?
4. In view of the deflection of cathode rays by a magnetic field, why did many 19th century physicists contend that they were not made up of moving charges?
5. How did the observed fact that cathode rays could penetrate thin layers of metal affect the controversy about the nature of the cathode rays?
6. How did Perrin contribute to the advancing frontier of knowledge about cathode rays?
7. What must be the relationship between the directions of electric and magnetic fields in order for an electron to pass through them both without deflection?
8. When a charged particle passes through an electric field, why are both its mass and its charge influential in determining how much it will be deflected?
9. What was the major significance of Thomson's research into the nature of cathode-ray particles?

Problems

A 1. In Fig. 16–4, assume the electrons are moving at a speed ⅙ that of light. For how long an interval is each electron subject to the electric field if the plates are 8.0 cm long?

2. If the potential difference between the plates in Fig. 16–4 is 500 V and the plates are 2.0 cm apart, what is the intensity of electric field expressed in V/m? (The field in V/m can be calculated from $E = V/s$)

3. In Problem 2, what is the force produced on the electron?

4. In Problems 1 and 2, what is the acceleration produced on the electron?

5. In Problems 1 and 2, what is the total deflection as the electron passes between the plates, where deflection is interpreted as the vertical distance moved during that interval?

B

6. A beam of electrons moving at 10% the speed of light goes between two plates which are 3 cm apart and have a potential difference of 600 V between them. During the time the electrons are between the two plates they experience an upward force. At the same time they cross a magnetic field whose direction and magnitude are such as to produce an equal and opposite downward force, so the beam has a net deflection of zero. What is the flux density of the magnetic field?

Discussion Questions

1. On p. 376 it was pointed out that the fact that cathode-ray particles penetrated solids was considered partial proof that the rays were electromagnetic waves. How could it be argued that electromagnetic waves penetrated solids?
2. What do you know about the nature of matter — knowledge which was not available to Thomson — which helps explain how electrons can penetrate solid matter?
3. In Fig. 16–5 what kind of charge on the plates will bend the ray in the direction shown?
4. Examine Fig. 16–5. If the upper plate is positive with respect to the lower plate, in which direction must the magnetic field be in order for the deflection forces due to the electric and magnetic field to be in opposite direction?

Precise Measurements of the Electron

16–4 The charge of the electron is accurately measured. Thomson had convinced the scientific world that cathode rays were made up of moving negative charges, that the charges moved very fast, and that they were a thousand or more times smaller in mass than the hydrogen ion. In short, he had identified a new fundamental particle, the electron. It remained for an American physicist, Robert Millikan, to make highly precise measurements of the charge of the electron. His ingenious technique, called the oil-drop experiment, is as interesting as it is important.

First, consider the movement of spherical droplets as they respond to gravity. (As is so often the case, a very advanced experiment — this one in particle physics — has its roots deep in pure mechanics.) You might expect that a droplet of oil, like any other falling body, would undergo uniformly accelerated motion. Actually, because of friction with the air, such a droplet very soon reaches a maximum velocity determined by its mass and size and by the viscosity of the air. The maximum velocity which a falling object reaches when falling through a fluid is called its terminal velocity. Raindrops reach a terminal falling velocity which, fortunately, is low enough that they do not injure people on whom they fall. As you know, droplets of mist have a much lower terminal velocity; they scarcely seem to fall at all.

When a falling spherical object has reached its terminal velocity, the force which makes it move (its weight) is exactly equal to the retarding force, which is proportional to its velocity. That is:

$$mg = kv$$

where m is the sphere's mass, g is the acceleration due to gravity, v is the terminal velocity, and k is a constant which depends on the size of the sphere and the viscosity of the air.

16–5 Millikan measures electron charge and mass with oil drops. The equipment for the Millikan oil-drop experiment to determine the charge of the electron is sketched in Fig. 16–6. Oil drops are produced by an ordinary atomizer above the upper plate, and a few of them slowly fall downward through the hole. The space between the plates is clean air, but it is protected from drafts and currents by completely enclosing it. A bright light shines in from the side to illuminate the tiny droplets, and their behavior is observed through a calibrated lens system — really a short-range telescope.

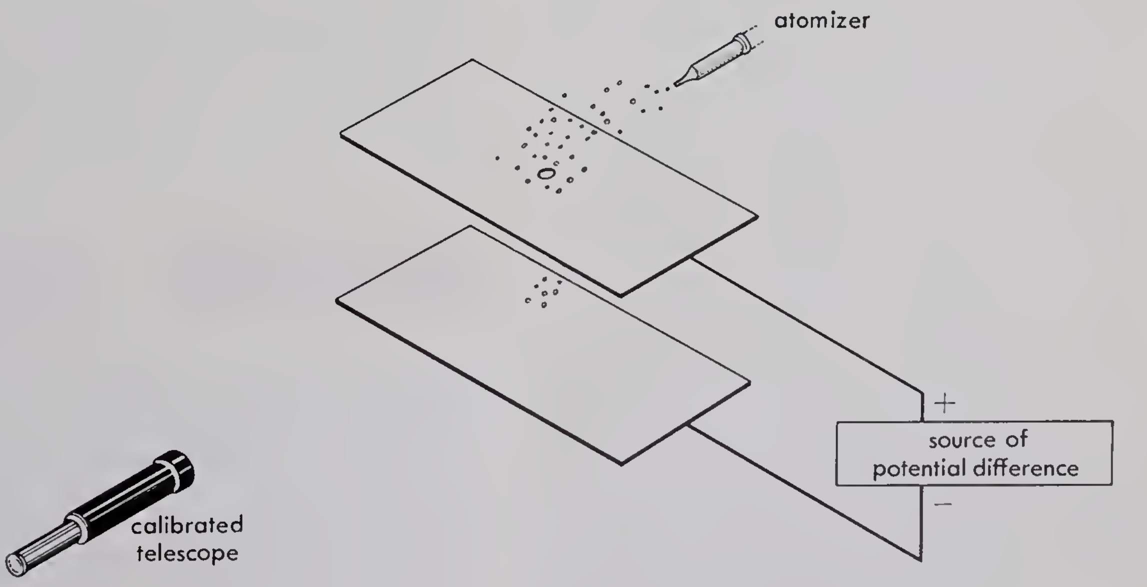
At the outset, you produce some oil droplets and pick out one through the telescope — one that is moving fairly rapidly, but not too rapidly to follow, for you wish to measure its velocity. Now you apply a potential difference across the two plates, with the top one being positive. Through the telescope you see that the droplet slows in its descent, or may even rise against the force of gravity. This is true because the droplets carry an electrostatic charge acquired by rubbing against the nozzle of the atomizer. If the droplet you have picked out does not happen to have such a charge, you select another one. You measure two velocities, one (v_O) in the absence of an electric field, and the other (v_E), with field.

Remember that when a sphere reaches its terminal velocity, the force which makes it move is equal to the retarding force. For the falling droplet without a field:

$$mg = kv_O$$

where k is a constant which depends on the size of the oil droplet, the density of the oil, the viscosity of the air, and other

Figure 16–6 In the Millikan oil-drop experiment a few oil droplets are allowed to drift through the tiny hole in the upper plate. They can be held motionless, or allowed to drift down or up by regulating the direction and intensity of the electric field between the plates. Their behavior is observed through the calibrated telescope.



factors. When there is an electric field, however, the force which makes the droplet move is EQ due to the electric field, upward, and mg due to gravity, downward. Hence the net force producing motion is the difference between the two, and the relationship between motion-producing force and retarding force is:

$$EQ - mg = kv_E$$

Adding the equations:

$$\begin{array}{rl} mg & = kv_O \\ EQ - mg & = kv_E \\ \hline EQ & = k(v_O + v_E) \end{array}$$

All the terms in this equation except Q can be measured or computed. Therefore Q, the quantity of charge on the oil droplet you are observing, can be calculated.

Now you know the total charge that happens to be on this particular droplet, but it may be due to one or several electrons. How do you find the charge on one electron? It is as though you had many bags each with a different number of identical balls. You can weigh the bags, but you cannot see inside to count the balls. Millikan solved the problem by repeated measurements of charge on droplets. He and his students made thousands of observations for individual droplets. The values which they obtained were something like these:

9.6×10^{-19} C
1.6×10^{-19} C
14.4×10^{-19} C
19.2×10^{-19} C
3.2×10^{-19} C
17.6×10^{-19} C
8.0×10^{-19} C
12.8×10^{-19} C
16.0×10^{-19} C
4.8×10^{-19} C
11.2×10^{-19} C
6.4×10^{-19} C

(Of course there were other values too. Besides, they were not all so even. They have been rounded off here for the sake of simplicity and clarity.)

Notice two things about this set of data: there is no value lower than 1.6×10^{-19} C, and if the values are arranged in order, each has a neighbor above and below it which is 1.6×10^{-19} C larger or smaller. This suggests that the basic unit of charge is 1.6×10^{-19} C. This, then, must be the charge on the electron. Since there are no values of charge which represent fractions of this, the electron must be indivisible and all electrons must have the same charge.

Another interesting variation to this experiment makes it even more convincing. Once in a while an oil drop you are watching will suddenly begin to rise faster than it formerly did, or perhaps slower. What has happened? You can conclude that it has gained an electron or two if its rate of rise increases, or that it has lost an electron or so if its rate of rise decreases. Perhaps the droplet has simply captured one out of the air, or maybe it has been struck by a cosmic ray and had an electron knocked out of it. You can make this happen if you carefully insert a tiny sample of radioactive material into the observation chamber. Whether the change of charge happens naturally or with your help, it turns out to have a magnitude of 1.6×10^{-19} C or a multiple thereof.

With this technique and later refinements of it, measurements of this important physical quantity, the charge of the electron, are still being made in many laboratories throughout the world. The accepted value for the charge of the electron is 1.60210×10^{-19} C.

Do It Now

Demonstrate the principle of deducing the charge of an electron from many observations of charge on droplets. Make a weight analogy using golf balls, marbles, or other similar objects, and paper bags. A suitable scale is also needed. Perhaps you can arrange it in the form of a class puzzle.

Once the charge of an electron is known, of course, its mass can be computed from the ratio of m/e as determined by Thomson. The best present value for the mass of the electron is 9.11×10^{-31} kg.

16–6 The values for the mass and charge of an electron are extremely important. The importance of man's knowledge of these physical constants cannot be overemphasized. The notion of a particle of matter far smaller than the atom, yet part of an atom, killed forever the idea that atoms were solid little balls. This paved the way for the modern concept of atomic structure as a compact nucleus surrounded by much space and a few electrons. These conceptual models are fundamental to an understanding of nuclear energy. Modern chemistry could not exist without the concept of the electron, and needless to say, neither could electronics.

Although the charge and the mass of the electron are quite precisely known, its size is not. Considerable talent and funds are now being devoted to the exploration of the electron's size. Maybe its size is not constant, or maybe it is a "fuzzy blob" for which definite size does not exist. Or perhaps there is no such thing as *size* for an electron. Possibly scientists should not think of it as a tiny speck of matter with charge, mass, and shape. It might be that the pure conceptual model breaks down here and one should think of an electron not in terms of how it looks, but rather in terms of how it behaves.

Self Check

1. How is Millikan's oil-drop experiment based on fundamental mechanical principles?
2. How do droplets in the oil-drop experiment acquire their electric charge?
3. Why is it not necessary to measure the mass of the droplets in the Millikan oil drop experiment?
4. What quantity was measured by the Millikan oil-drop experiment?
5. What other quantity could be accurately determined from Millikan's experiment?
6. Why did accurate measurement of charge and mass of the electron force a change in theories about the atom?

Problems

Ⓐ If an oil droplet weighs 35 micrograms, what is the retarding force in newtons when it reaches its terminal velocity?

Discussion Questions

1. In reviewing the experiments of Geissler, Crookes, Thomson, and Millikan, what examples can you cite in which the scientific research depended heavily on technological competence?
2. It is said that a typical man falling without parachute from an airplane falls no faster than about 200 mi/hr, regardless of the height from which he falls. How do you explain this in terms of what you know about uniformly accelerated motion of freely falling bodies?
3. In the 1930's the charge on the electron was computed in a different way, using the results of experiments designed to measure the wavelength of x-rays. This new value for e was about 0.6% higher than Millikan's. Both Millikan's experiment and the new ones had been done very carefully, and a measurement error this large seemed quite improbable. However, in calculating his results, Millikan had used a number of constants measured by other people. Eventually it was discovered that one of these had been inaccurately measured. When the correct value was used with Millikan's data, his results agreed with those from the newer experiments. Reread the account of Millikan's experiment, and list the constants he used that he did not measure himself during the experiment.

Acceleration of Charged Particles

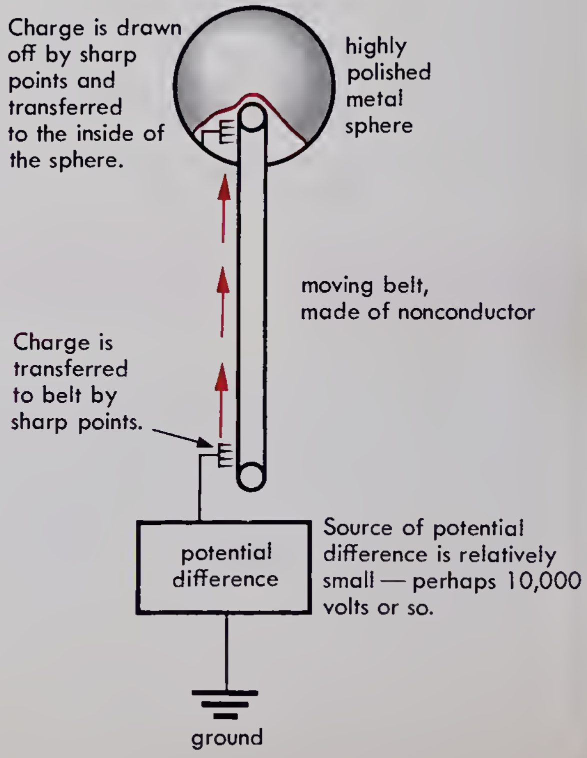
16–7 High-energy particles aid in the study of other particles. One of the most active frontiers of physics today is that of particle research — the study of particles which make up atomic nuclei, and of high-energy particles which make up cosmic rays, as well as the effects of particles on other particles.

What kinds of tools are needed to probe subatomic particles? One technique is to bombard the nuclei of atoms with "bullets" whose energy is great enough to alter the nucleus. The "bullets" themselves must be subatomic particles — protons, neutrons, deuterons, alpha particles, etc. Also needed is a "gun" to fire the "bullets" — that is, an accelerator to direct the subatomic particles at high speed toward their target. For obvious reasons such **particle accelerators** have often been called "atom smashers." An accelerator is a device designed to accelerate subatomic particles up to enormous velocities and deliver them to the desired place under controlled conditions.

16–8 The Van de Graaff generator accumulates electric charge mechanically. Particle accelerators use electric fields to set electric charges in motion. If an electron (or any other particle of one unit of negative or positive charge) is accelerated through a potential difference of 1,000,000 volts, it acquires an energy of 1,000,000 electron volts. The problem is, how does one prepare such a strong electric field? How can one electrode of an accelerator be given a potential of 1,000,000 volts with respect to another electrode? If you rub a plastic rod with fur, the rod becomes charged negatively and the fur positively. Now if you touch an insulated metal sphere with the rod, you give the sphere a negative charge. If you touch a similar metal sphere with the fur, you give that sphere a positive charge. You might continue the process, first rubbing the rod with the fur and then adding to the charges on the spheres, until there is a potential difference of several thousand volts between the two spheres. This is the principle of the generator developed in 1931 by Van de Graaff at Princeton University.

A Van de Graaff generator uses an endless belt to carry charges — positive in some machines, negative in others — to the inside of a hollow metal sphere. When they arrive on the inside of the sphere, they are conducted to the outside surface, where they are stored. As shown in Fig. 16–7, the initial charge is supplied by batteries or some other source of perhaps 10,000 to

Figure 16–7 This diagram of a Van de Graaff generator shows that basically it is an endless belt which carries charges (either positive or negative) from the source below to the metal sphere above. The sphere is supported by a nonconducting structure.


Charge is drawn off by sharp points and transferred to the inside of the sphere.
highly polished metal sphere
moving belt, made of nonconductor
Charge is transferred to belt by sharp points.
potential difference
Source of potential difference is relatively small — perhaps 10,000 volts or so.
ground

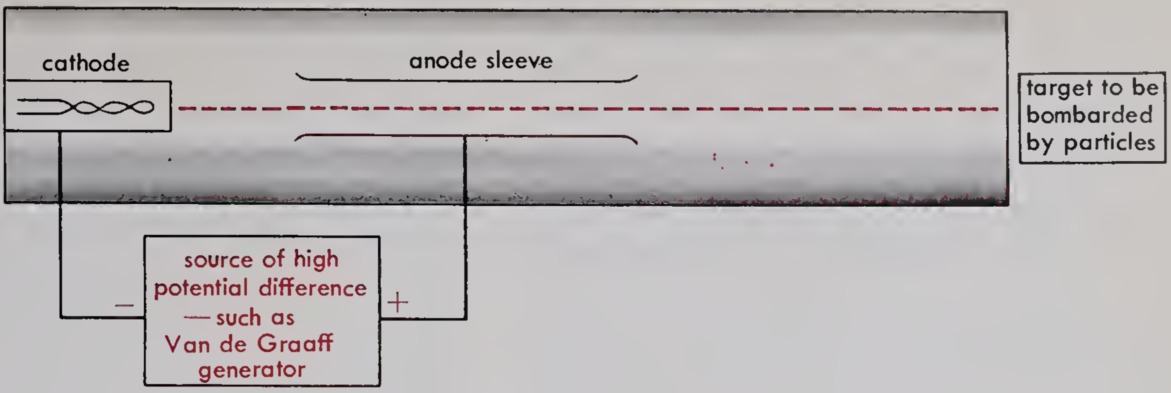

cathode
anode sleeve
target to be bombarded by particles
source of high potential difference — such as Van de Graaff generator
−
+

Figure 16–8 This diagram suggests how a Van de Graaff generator might be used in a simple particle accelerator. Notice that the accelerating anode is a hollow sleeve. Therefore, the particles are accelerated by the anode and go through it to the target.

50,000 volts potential.[*] The charge is transferred to the moving belt from a set of sharpened metal points which do not quite touch the belt. (Charges at high potential tend to leak into air from sharp points.) The belt, a rubber or plastic band moving perhaps 80 to 100 m/sec, carries the charges upward where they are removed by the upper set of sharpened metal points. If the sphere is very large and highly polished, the potential difference between the sphere and the bottom of the generator can be made as high as 6 or 8 million volts without having an uncontrolled spark discharge from the outside of the sphere.

16–9 The linear accelerator uses alternating electric fields to accelerate particles.

The Van de Graaff generator can be used as an accelerator for apparatus such as that shown in Fig. 16–8. This is really nothing but a glorified cathode-ray tube (or a tube for any charged particle). To accelerate the particles up to extremely high speeds it is necessary to have a high potential difference between the cathode and the hollow anode sleeve. A Van de Graaff generator is a typical source of high potential difference in applications such as this.

At first glance it might appear that the maximum potential difference that can be used in such an accelerator is that which a Van de Graaff or similar generator can produce. This is of the order of magnitude

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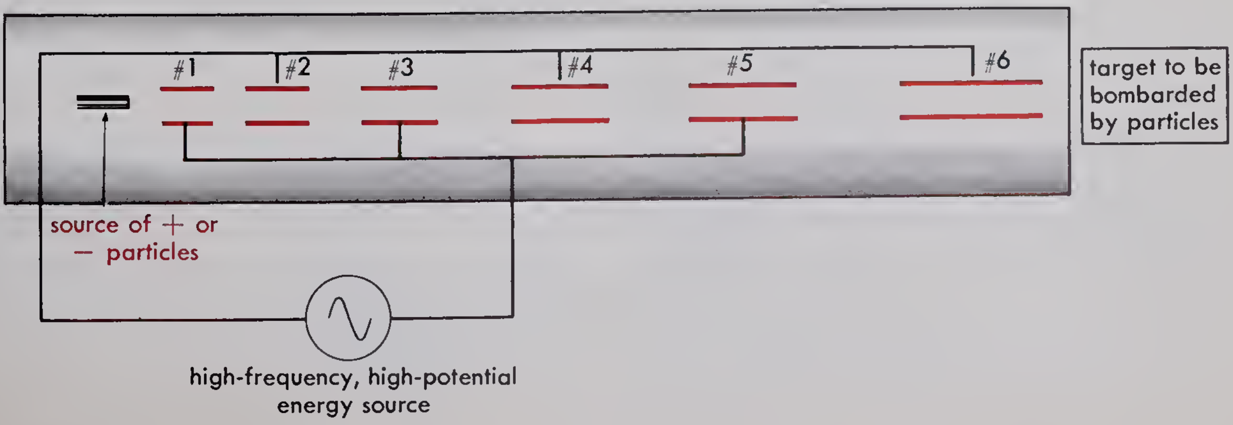
[*] In very small, demonstration-type Van de Graaff generators, this initial charge is usually supplied by the rubbing action (static electricity) of the belt on the lower drum.

Figure 16–9 This linear accelerator uses a series of hollow sleeves. A negative particle is accelerated by the positive potential of sleeve No. 1. While it coasts inside No. 1, the potentials reverse. When it emerges from No. 1, No. 2 has become positive and No. 1 is negative. Thus the particle is accelerated toward No. 2. Successive sleeves, and the spaces between them, are longer because the particle is moving faster as it gets farther and farther from the source.


#1
#2
#3
#4
#5
#6
target to be bombarded by particles
source of + or − particles
high-frequency, high-potential energy source

of several millions of volts. However, this available potential difference can be multiplied in a particle accelerator. One device which permits this is the **linear accelerator**.

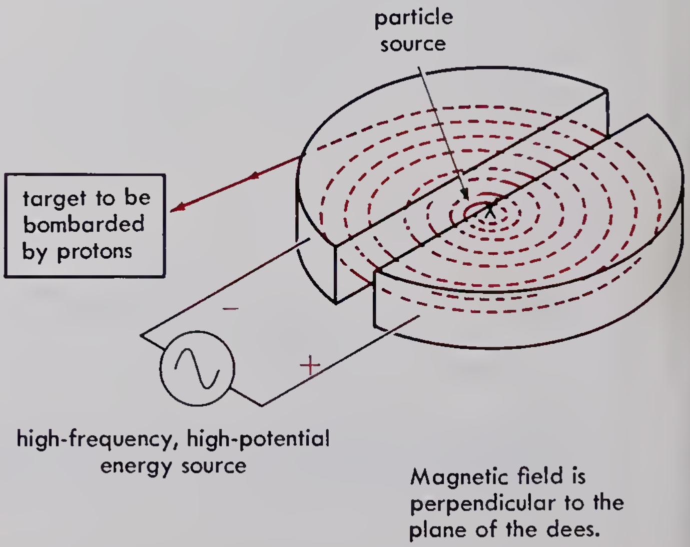
In thinking about a linear accelerator, it is important to realize that in Fig. 16–8 the particle experiences an accelerating force only when it is between the source of particles and the accelerating electrode. Once inside the sleeve it merely coasts. The potential of the sleeve can be reduced or even reversed without affecting the particle. In a linear accelerator this is precisely what happens. In Fig. 16–9, assume that the potential difference available is 1,000,000 volts. As the electron accelerates between the source and sleeve No. 1, it acquires 1,000,000 electron volts (1 meV) of energy. While it is inside the first sleeve, the polarity of the sleeve reverses because the potential difference is supplied by a high frequency alternating source. Now the first sleeve is 1,000,000 volts negative with respect to the second sleeve. As the electron coasts out of the first sleeve it is again accelerated by a potential difference of 1,000,000 volts. By the time it gets inside sleeve No. 2 it has a velocity corresponding to an energy of 2 meV. This process is repeated down the line of sleeves whose potential is constantly reversing.

Linear accelerators can be used to provide high velocities for any kind of charged particles. The resulting beam of particles is easily controlled and concentrated on its target. At present the largest linear accelerators provide particles whose energy is of the order of a billion electron volts.

16–10 The cyclotron guides charged particles by using a magnetic field. The **cyclotron**, invented by Lawrence at the University of California in 1930, was the first of the really big "atom smashers." This device accelerates positively charged particles (usually protons) from one charged electrode to another, just as does a linear accelerator. As in the linear accelerator, the electrodes are hollow. During most of the time the particles are *inside* the electrodes; their speed increases only while they are *between* the charged electrodes. Unlike the linear accelerator, however, the cyclotron uses only two accelerating electrodes. It gives the particles repeated "kicks" by guiding them back and forth from one electrode to the other. Although acceleration is accomplished by the charges on the electrodes, the guidance of the charged particles is done by means of a magnetic field.

The method of operation of a cyclotron is shown in Fig. 16–10. Charged particles enter the cyclotron almost at the center, between two electrodes shaped like hollow half-pillboxes and referred to as "dees" because of their resemblance to the letter "D." At the instant shown, a proton is accelerated toward the upper dee which is now negative. However, inside the dee there is a strong magnetic field perpendicular to the plane of the dees, so the proton

Figure 16–10 This diagram illustrates the basic operation of a cyclotron. Particles are accelerated by the field between the hollow dees, and kept in a curved path — an outward spiral — by a magnetic field perpendicular to the plane of their motion.


particle source
target to be bombarded by protons
−
+
high-frequency, high-potential energy source
Magnetic field is perpendicular to the plane of the dees.

follows a tight circular path until it has turned 180°. It is now ready to cross the gap between dees. However, the potential between dees has reversed so that the lower one is now negative with respect to the upper one. Hence the charge is accelerated as it crosses the gap. Having now a higher velocity, it moves in a slightly larger circle. After another half-revolution the same procedure is repeated. The particle thus moves in an outward spiral. The potential difference between the dees may be 100,000 volts or so. Thus by the time the particle has made many trips, it has an energy of many million electron volts. Modern modifications of the cyclotron can accelerate particles such as protons, deuterons, and alpha particles up to speeds corresponding to about 500 meV.

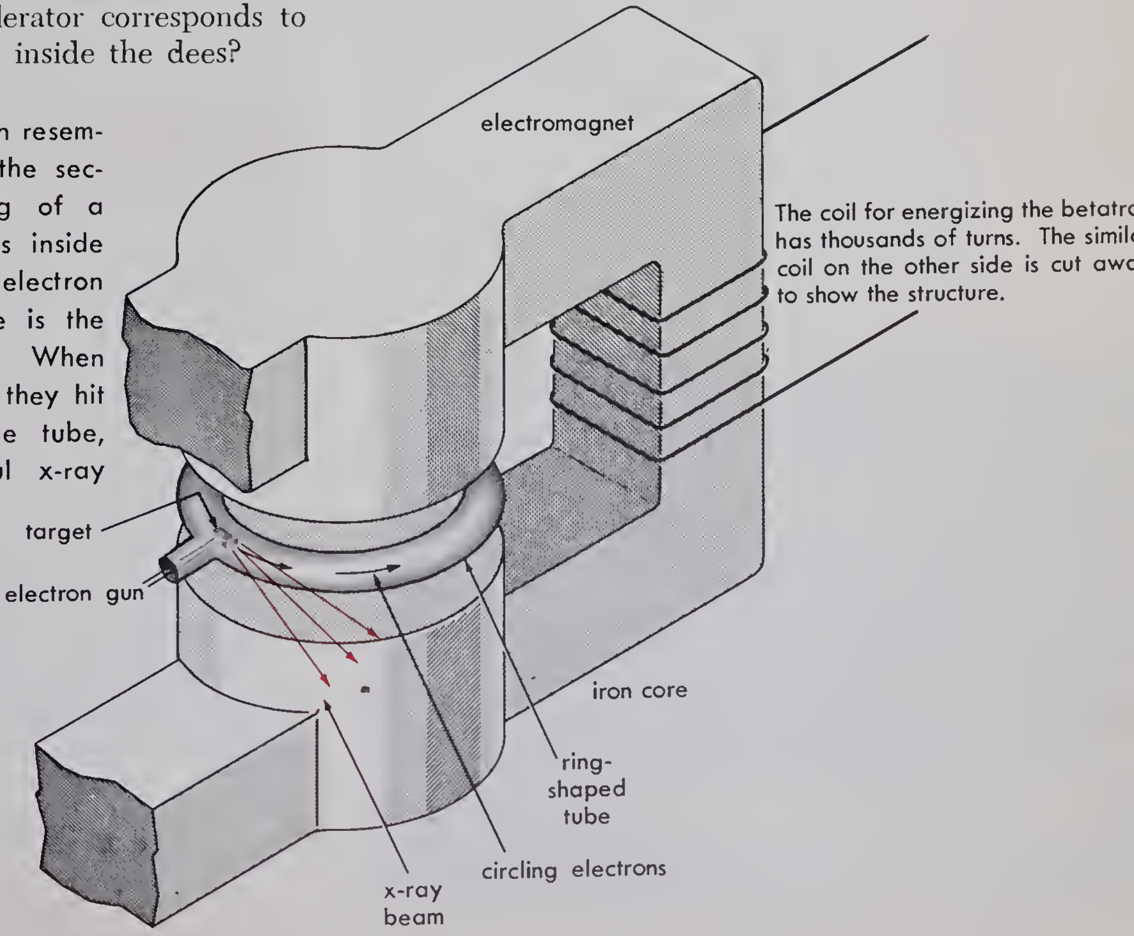
Do It Now

1. In some respects the cyclotron is much like the linear accelerator. What part of a linear accelerator corresponds to the gap between the dees of the cyclotron? What part of a linear accelerator corresponds to the path of a particle inside the dees?
2. During what part of its path in a cyclotron is a particle accelerated?
3. As a proton spirals at a faster and faster speed in a cyclotron, it still takes the same time to cover each half-circle because it has to go a greater distance. Why does this fact make operation of the cyclotron simpler than it would otherwise be?

16–11 The betatron accelerates electrons by a changing magnetic field. The **betatron** is a special kind of vacuum tube which can accelerate electrons up to energies corresponding to about 100 meV. It is not as powerful as cyclotrons and other large accelerators, and it is much smaller and far less expensive to build. Its name comes from the fact that it accelerates electrons, which are also called beta rays.

The operation of a betatron is diagramed in Fig. 16–11. A doughnut-shaped vacuum tube, which corresponds to the secondary winding of a transformer, is placed between

Figure 16–11 The betatron resembles a transformer, with the secondary winding consisting of a circling beam of electrons inside an evacuated tube. An electron gun sealed into the tube is the source of the electrons. When they are going very fast, they hit a target, also inside the tube, and produce a powerful x-ray beam.

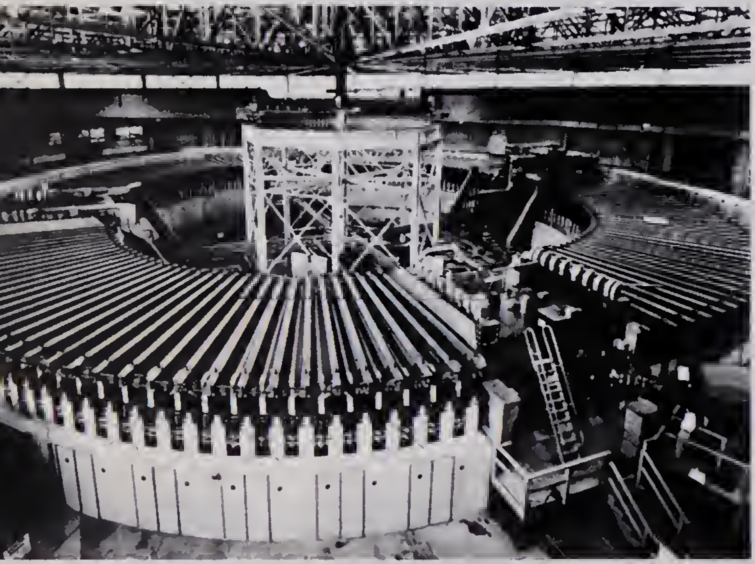


the pole-pieces of a large electromagnet. This is commonly energized by 60-cycle current. Electrons are injected into the betatron with velocities corresponding to some 50,000 eV. They are then accelerated during the quarter-cycle (1/240 sec) while the magnetic flux grows from 0 to maximum. They are accelerated because they represent a "loop of conductor" through which magnetic flux is changing. (Remember from Chapter 12, $V = \frac{\Delta\Phi}{\Delta t}$). During this time an electron may make a quarter-million round trips acquiring energy up to 100 meV. They are then deflected to hit a target. Note that the electrons are accelerated by *changes* in magnetic field but are kept in a circular path by the *existence* of the magnetic field.

16–12 The synchrotron uses both charged electrodes and changing magnetic fields. As you have seen, the cyclotron permits particles to follow an ever-widening spiral as they are accelerated. In the betatron, however, the path of the whirling electrons is kept at constant radius by varying the intensity of the magnetic field as the particle increases its velocity. In the linear accelerator and the cyclotron, acceleration is produced by charged electrodes; in the betatron, acceleration results from a changing magnetic field within the doughnut-shaped betatron tube. The most powerful accelerators in use today employ both of these techniques to control particles — charged electrodes and changing magnetic fields. Charged electrodes accelerate the particles as they whirl repeatedly about a near-circular path, while a changing magnetic field keeps them in the same path revolution after revolution.

There are other complications, too. As particles approach the speed of light, their mass increases (see Chapter 4). Thus the energy added to them by the accelerating fields is not entirely represented by increased velocity, but in part by increased mass. That is, the increase in velocity of such particles is less than would be expected were it not for the relativistic mass increase. To deal with this, the rate of alternation of potential difference on the accelerating electrodes must be decreased as the particles get nearer and nearer to the speed of light. Because of this synchronization of electrode frequency and moving particle, accelerators such as these are called **synchrotrons** (Fig. 16–12).

Figure 16–12 This synchrotron at the University of California is called a bevatron because it accelerates particles to 6 billion electron volts (beV).



Self Check

1. Why do scientists wish to accelerate charged particles?
2. Where does a Van de Graaff generator get the original charge that is carried on the moving belt up to the sphere?
3. How does a linear accelerator effectively multiply the potential difference of its source of electric energy?
4. What is the advantage of accelerating particles in a circular or spiral path?
5. In a cyclotron in which the magnetic field is constant, why do whirling particles follow a spiral path rather than one of repeating circles?

6. In a betatron and a synchrotron, how are accelerating particles kept from following a path of an expanding spiral?
7. How does the betatron differ from the cyclotron in its method of producing acceleration of charged particles?
8. Which of the types of accelerator discussed in this section is designed to work with particles that show an appreciable increase in mass due to high velocity?

Problems

A 1. In a certain linear accelerator, the fourth sleeve is 3.0 cm long, and the velocity of a particle within it is known to be 2.0×10^5 m/sec. Find the length of a sleeve at a point where the velocity of the particle is 1.0% of the speed of light?

B 2. Assume that in a certain kind of accelerator the effects of increase of mass with increasing velocity are not troublesome until the speed is 95% of the speed of light. How much energy can be given to an electron before trouble is encountered? How much energy can be given to a proton?

Discussion Questions

1. Why cannot neutrons be accelerated in the machines discussed in this section?
2. In a Van de Graaff generator, what is the source of the energy represented by the stored charge?

Semiconductors

During the last quarter-century there has been increasing emphasis on a field known as **solid-state physics**. Solid state, of course, refers to solids, as contrasted with liquids and gases. Solids have many important physical properties — hardness, thermal conductivity, and others. Solid-state physics is concerned with the structure and behavior of atoms and molecules in solids, for this structure and behavior determine the physical properties. Research in solid-state physics is already producing many practical applications in such areas as transistors, thermoelectric devices, and crystallography.

16–13 Semiconductor elements belong to a certain group. You already know that different materials vary greatly in their ability to conduct electricity. They range from extremely good conductors to extremely poor conductors (excellent insulators). A great many materials lie somewhere between these extremes. Of special interest are the recently explored semiconductors. The **semiconductor elements** are all members of the same chemical group. (Chemists call this Group IVa.) The feature which they have in common relates to their atomic structure.

As you know, an atom has a central nucleus containing protons and neutrons, with electrons orbiting around it. These orbiting, or planetary, electrons may be thought of as being in various **energy levels**; often it is said that they are arranged in concentric shells. The innermost shell, or lowest energy level, has room for two electrons, and the next one has room for eight. Oxygen, for example, has a total of eight electrons; two are in the inner shell and six in the outer shell, where there is room for eight. Representations of the oxygen atom and the mercury atom are illustrated in

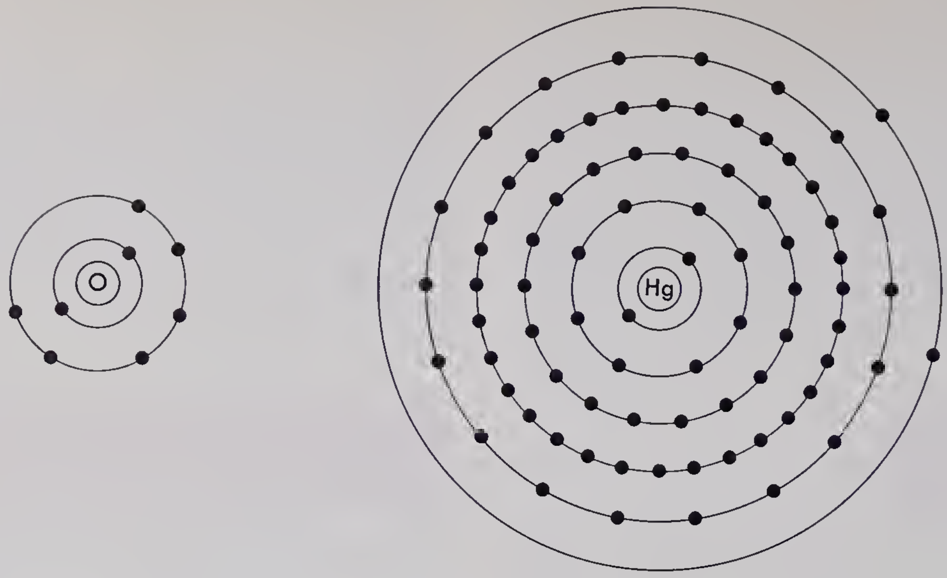


Figure 16–13 At left is a diagram of an atom of oxygen. Its eight planetary electrons are arranged two in the first shell, and six in the second, where there is room for eight. In the mercury atom at right, the 80 planetary electrons are arranged in shells of 2, 8, 18, 32, 18, and 2. This outermost shell has room for eight electrons. The concentric circles shown do not represent the paths of electron orbits, but rather the energy levels of the various groups of electrons.

Fig. 16–13. Almost all atoms have room for just eight electrons in the outer shell.

The semiconductor elements all have four electrons in the outermost shell. When a semiconductor element such as germanium is in crystal form, the four outer electrons are shared by neighboring atoms, thus creating filled-up shells, as suggested in Fig. 16–14. Since all the outer-shell electrons are bound into this interlocking structure, none of them is free to move. Indeed, if semiconductor elements are extremely pure, they are essentially insulators.

16–14 Certain impurities contribute extra electrons. If a very small amount of certain impurities is added to a semiconductor crystal, such as germanium (Ge), it behaves quite differently from pure germanium; the process of adding these impurities is called **doping.** Consider the element arsenic (As), much like germanium, but which has five electrons in the outer shell. The result of traces of this kind of impurity is shown in Fig. 16–14a. Notice that there is an electron which has no place in the crystal structure and thus is relatively free to move about within the crystal. Indeed, it behaves much like a free electron. This makes the doped germanium a moderately good conductor of electric current.

Impurities which provide extra electrons are known as **donors** Semiconductor elements which have been doped with donor impurities are conductors because of the presence of *negative* carriers of current, that is, electrons. Hence such materials are referred to as **n-type semiconductors**

16–15 Certain other impurities contribute positive carriers. What happens when a germanium or other semiconductor crystal is doped with a suitable element which has only three electrons in its outer orbit? Aluminum and indium are such impurities. The result is shown in Fig. 16–14b. Here the impurity provides the germanium with vacant spots in the crystal structure,

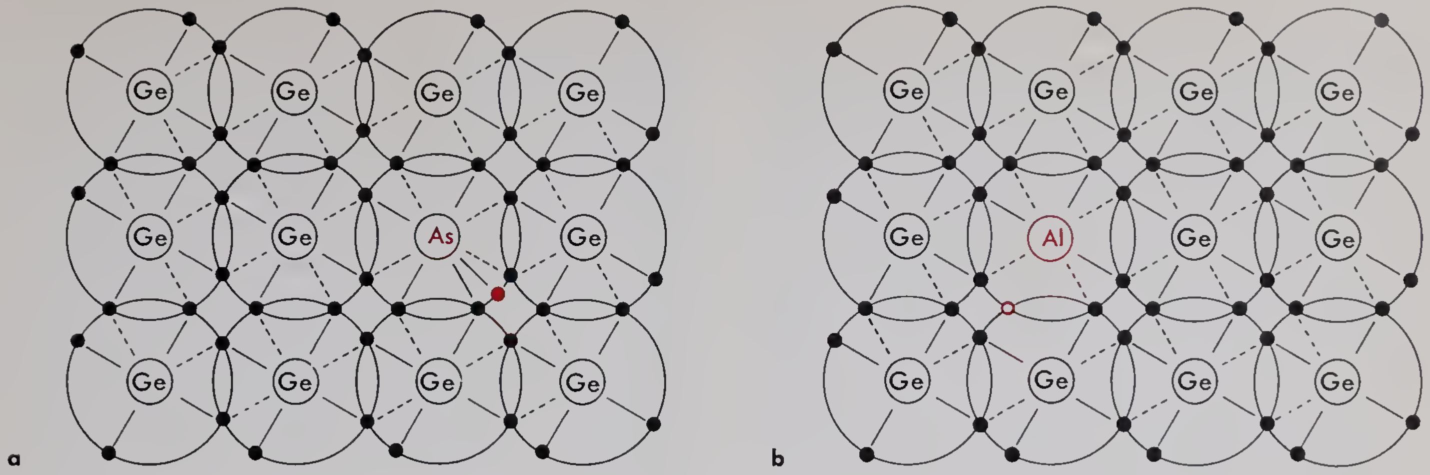
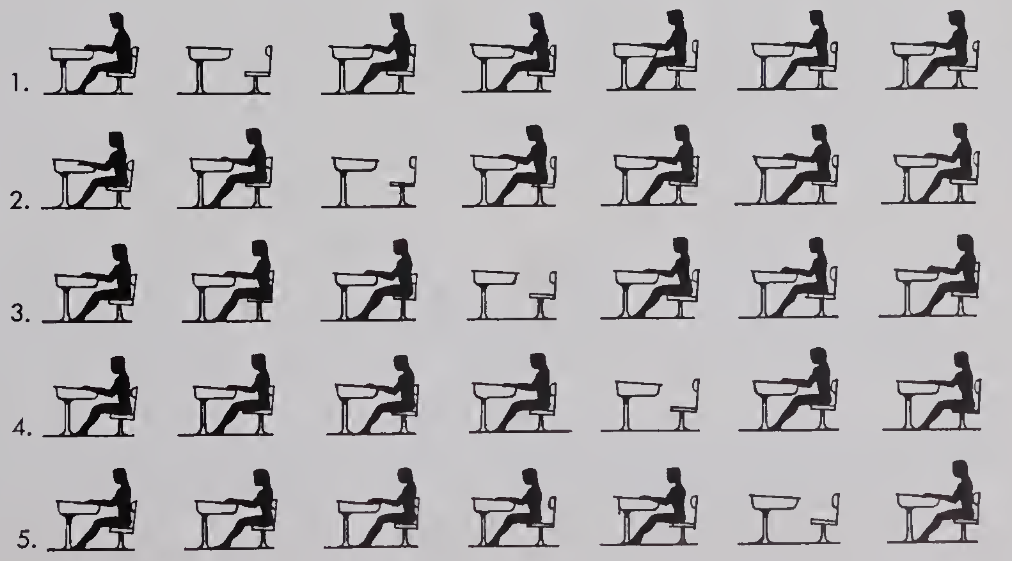


Figure 16–14 In these drawings, the electrons in the outer shells of each atom are represented by dots. Each electron belongs to the atom to which it is attached by the solid line. At the same time the electron is shared by the atom to which it is attached by a dashed line. In a pure crystal of germanium every atom thus has 4 electrons of its own, plus 4 shared electrons, which complete the outer shell. In **a** an atom of arsenic, with 5 outer-shell electrons, provides an extra electron. In **b** an atom of aluminum, with only 3 outer-shell electrons, creates a hole in the crystal. The extra electrons and also the holes act as current carriers in semiconductors.

literally *holes.* Can these holes act as electric carriers in a manner similar to excess electrons? Can vacancies — literally nothing — play an active part in the explanation of semiconductor behavior? They can.

To see how a hole can move, look at Fig. 16–15. In line 1, the first student has an empty desk behind him. The next student moves up to fill the hole, leaving a hole between the second and third students. Now the third student moves up, and the empty desk travels toward the right one more step. You can think of the action as that of students moving from right to left or of the empty desk in the line moving from left to right. In the same way, the holes in a

Figure 16–15 This diagram shows how a "hole" in a line of students at desks can move. Actually, of course, the "hole" movement from left to right can be explained in terms of students moving from right to left. In transistor theory, however, it is useful to keep one's attention on the holes in p-type semiconductors.



crystal can move. Consider the hole in Fig. 16–14b, for example. If the germanium crystal is connected to a battery so that the right side of the crystal is negative and the left side positive, an electric field is created that tends to force electrons from right to left. As a result, the electron on the right of the hole may jump over into the hole. The hole moves one step to the right. The next electron jumps in, and the next, and the next. The hole migrates to the right across the crystal.

Holes may be considered to have a positive charge. Remember, in the analysis above and in Fig. 16–14b, the holes do migrate toward the negative battery terminal at the right. Actually, of course, the holes are nothing and can have no charge. But compared to electrons, zero charge is positive. In a similar way, a penniless beggar is wealthy compared to the financier who is deep in debt.

Impurities which contribute holes to semiconductor materials are said to be **acceptors.** Semiconductor crystals which are doped with acceptor impurities, and which therefore have holes as carriers in the crystal structure, are referred to as **p-type semiconductors.** They have positive carriers which move toward a negative potential, as contrasted to the negative carriers (electrons) of n-type germanium, which move toward a positive potential. In many ways n-type germanium and p-type germanium may be considered as electrical opposites.

Physicists think of these explanations of the behavior of semiconductors as a *conceptual model.* The model may not be complete in every detail. For that matter, it may well be that a simple mechanical model is as impossible here as when you were studying nuclear reactions. But the conceptual model often acts as a guide and has great values, particularly when you remember its limitations.

16–16 A semiconductor junction passes current in one direction only. Suppose a piece of n-type germanium and one of p-type germanium are in intimate electric contact, as shown in Fig. 16–16. How will they behave as part of a circuit? The results may be surprising; they are certainly useful. In Fig. 16–16a the n-section is connected to the negative terminal of a dry cell, and the p-section to the cell's positive terminal. In this electric field, the negative carriers (electrons) and the positive carriers (holes) are both forced toward the p-n junction. At the boundary surface, electrons from the n-section move into the holes in the p-section. A **p-n junction** subjected to this electric polarity is said to be "biased in the forward direction" or "front-biased." At a front-biased junction, electrons flow from the n-section to the p-section. This electron flow is electric current.

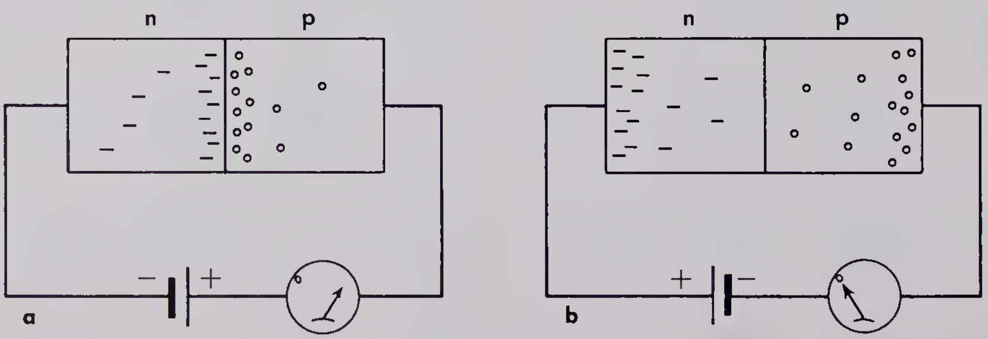


Figure 16–16 a. In this circuit, negative and positive carriers are drawn toward the junction. There the electrons jump into the holes, creating a current. **b.** Here both kinds of carriers are attracted away from the junction, so there is no current.

In Fig. 16–16b, on the other hand, the connections to the cell are reversed. Now both positive and negative carriers are forced away from the p-n junction. Neither electrons nor holes can now cross the boundary surface and current is essentially zero. A p-n junction subjected to such an electric polarity is said to be "back-biased" or "reverse-biased."

This principle of one-way current underlies the operation of semiconductor rectifiers, which are made from n- and p-doped pieces of semiconductor crystal in intimate contact with each other. A semiconductor rectifier behaves much like a vacuum tube diode and is referred to as a **crystal diode**. The n-section is frequently called the cathode of the diode, and the p-section the anode. Diodes like these are extremely useful in radio circuits and as rectifiers in alternating-current measuring instruments (see Chapter 13).

Do It Now

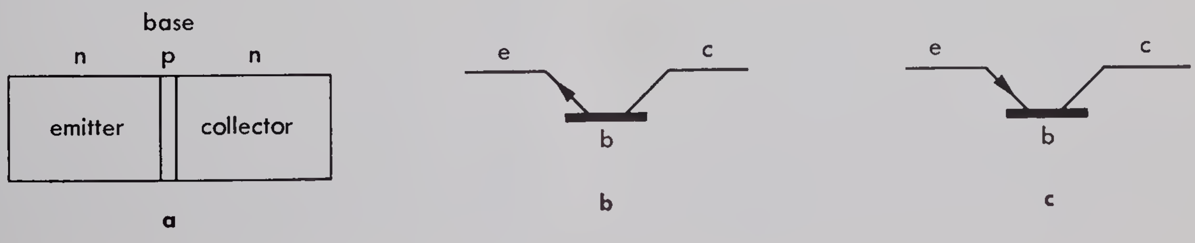
Invent a kind of "people analogy" to the semiconductor junction just described. You might do it with one county where there are nothing but bill collectors, and an adjacent county where there are nothing but people who want to pay their bills.

16–17 Transistors are made of semiconductors. A p-n junction of semiconductors permits electrons to flow when front-biased but not when back-biased. It behaves much as does a vacuum tube diode. A third section can be added to a crystal diode to make it into a device capable of electronic control functions. Such a three-section semiconductor device is called a **transistor**.

The structure of a common transistor is shown in Fig. 16–17a. Note that there are three sections assembled like a sandwich. On the left is a section of n-type germanium termed the **emitter**. At the right is another n-section called the **collector**. Although these look alike in the diagram, there is usually a difference in the exact way they are doped; they are not interchangeable. Between the two is a very thin p-type section called the **base**. The entire device may be the size of a pin head. Commercial transistors are usually embedded in plastic or encased in metal. The complete device is scarcely bigger than half a pea.

The principles that underlie the operation of a transistor are the same as those of the crystal diode. Figure 16–18 shows how a transistor is connected in a simple circuit. Note that the right junction is back-biased, while the left one is not biased at all because the switch is open. The dis-

Figure 16–17 **a.** This is a diagram of the construction of a typical transistor. Actually there are differences between the emitter and the collector so they are not usually interchangeable as the diagram might suggest. **b.** This is the schematic symbol for an npn transistor. **c.** This symbol for a pnp transistor is an electrical opposite of the one in **b.** The existence of "mirror images" in transistors makes possible the design of many useful circuits which are impossible with vacuum tubes, since there are no "positron tubes" which are mirror images of "electron tubes."



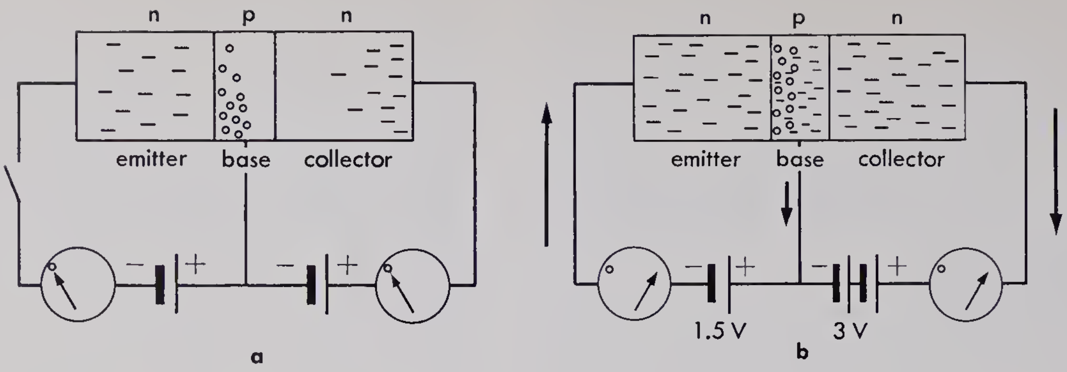


Figure 16–18 In this circuit note that the emitter-base junction is front-biased, while the collector-base junction is back-biased. At left there is no current in the emitter-base circuit since the switch is open. Because of carrier distribution in base and collector, there is also no current in that circuit. At right, however, the switch has been closed, and the base-collector junction is no longer a barrier to current. In this way, one current (input current from emitter to base) has controlled another current (output current from base to collector).

tribution of electrons and holes is shown in Fig. 16–18a. Obviously there is no current across the base-collector junction; that is, the collector current is zero.

Now in Fig. 16–18b the switch in the base-emitter circuit is closed. Because this junction is front-biased, electrons cross the junction into the very thin base. Once they are in the base, these electrons are extremely close to the collector, which is positive with respect to both the base and the emitter. In the circuit of Fig. 16–18b, nearly all of the electrons which leave the emitter go *through* the base and on into the collector. In the illustration, the sizes of the arrows by the leads to the emitter, base, and collector indicate the relative intensity of current in those leads. Here about 95% of the emitter current goes on through the collector; only about 5% goes through and out of the base. Notice that Kirchhoff's rules apply to this circuit.

For a given potential difference across the base-collector junction, the magnitude of the collector current depends on the magnitude of the emitter current. The greater the emitter current, the greater the collector current is. But remember, the emitter current depends on the potential difference across the emitter-base junction. Therefore, if a signal voltage is applied to the emitter-base junction, the collector current fluctuates accordingly. The pattern of input signal is reproduced in the output signal.

Many circuits can be built around transistors; one of the most interesting is shown in Fig. 16–19a. Here the input or controlling circuit includes a 1.5-volt cell, a rheostat, a meter, and the emitter-base junction. The output or controlled circuit includes a 3-volt battery, a meter, and both junctions of the transistor.

As in the previous circuit, there can be no collector current when the emitter current is zero. As the rheostat is adjusted, the potential difference across it varies, and (by Kirchhoff's first rule) the front bias across the emitter-base junction also varies. This in turn controls the number of electrons which go from the emitter through the base to the collector.

The circuits of Fig. 16–18 and 16–19 use n-p-n transistors. If p-n-p transistors are used, the polarity of the batteries must be reversed. The results are the same except

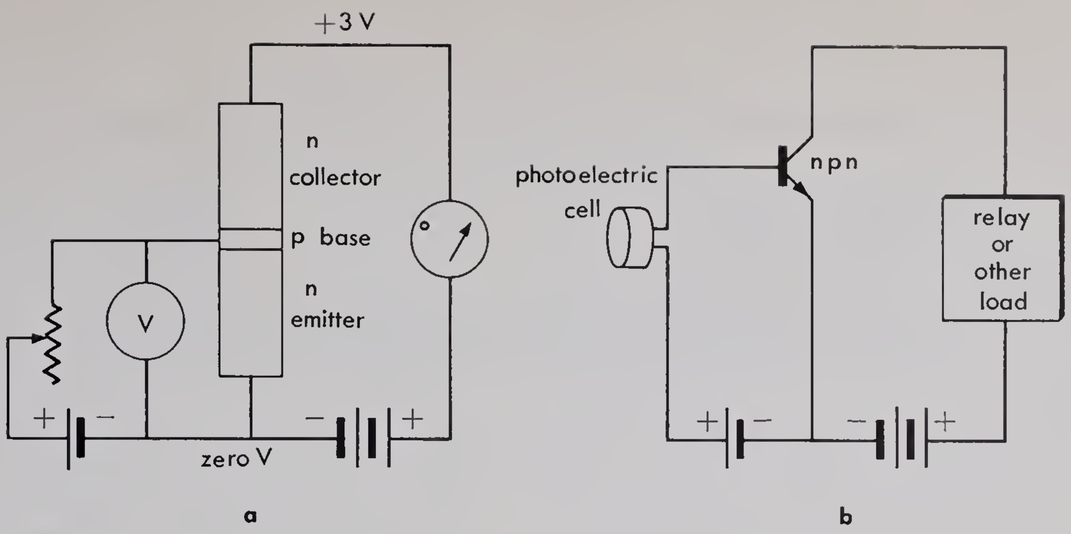


Figure 16–19 a. In this circuit the rheostat controls the current in the emitter-base circuit and the potential difference between emitter and base. As this front-biased potential difference fluctuates, the current in the collector circuit varies with the same pattern. **b.** The circuit of **a** can be applied to a useful amplifier circuit. Here the front bias is determined by the performance of the photoelectric cell. Small changes in the current which it produces result in large changes in the output current — large enough to operate a relay or other device, which the photoelectric cell itself could not. Notice that the circuit of Fig. 16–18 does not amplify the current, but that this one does.

that the movement of holes is substituted for the movement of electrons.

16–18 Vacuum tubes and transistors differ in their characteristics. It is very interesting to compare vacuum tubes, which were developed in the early years of this century, with the more recent crystal diodes and transistors. It is tempting to conclude that transistors are the successors to vacuum tubes. This is not strictly true. There are a multitude of uses for both kinds of electronic control devices.

In many situations vacuum tubes are superior to transistors. They can be made to handle much greater power; and they withstand higher temperatures.

The advantages of transistors are many: (1) Because they require no cathode heater, they require no source of heater power and no warm-up time, they consume very little power, and they do not get as hot as vacuum tubes. (2) Because their parts are fused to each other, they are extremely small, they are more resistant to shock and vibration, and they have almost indefinite life. (3) They operate on energy sources with low potential difference, often a very few volts.

Self Check

1. What feature of germanium makes it and certain other elements semiconductors?
2. Why would a pure crystal of a semiconductor be a poor conductor of electrons?
3. How can an impurity contribute positive carriers to a semiconductor crystal?
4. When a p-n junction is front-biased, which section is connected to the positive terminal of a battery?
5. Why does not a back-biased crystal diode conduct, even though each of its wafers contains current carriers?
6. What is one use for a crystal diode?
7. In the circuit of Fig. 16–19, how do the electrodes (wafers) of a transistor roughly correspond to the electrodes of a triode?
8. In what ways are vacuum tubes superior to transistors? In what ways are transistors superior?

Other Results from Solid-State Research

16–19 Thermocouples have been greatly improved. If you connect an iron wire to a copper wire, as shown in Fig. 16–20a, with a galvanometer in the circuit, and then heat one of the copper-iron junctions, you will find that the galvanometer deflects. The hotter you make one junction as compared with the other, the greater is the current in the galvanometer. A highly sensitive galvanometer will deflect even when one junction is warmed merely by holding it in your hand. This type of circuit, containing two junctions of dissimilar conductors each at a different temperature, is known as a **thermocouple**; it converts heat energy directly into electric energy. It is frequently used for measuring temperature.

Although the thermocouple has been known for nearly a century and a half, until recently its low efficiency (below 3%) kept it from being a practical device for the conversion of electric energy. However, with the introduction of semiconductors and an increasing knowledge of their behavior, thermocouples are now used as a means of providing electric power.

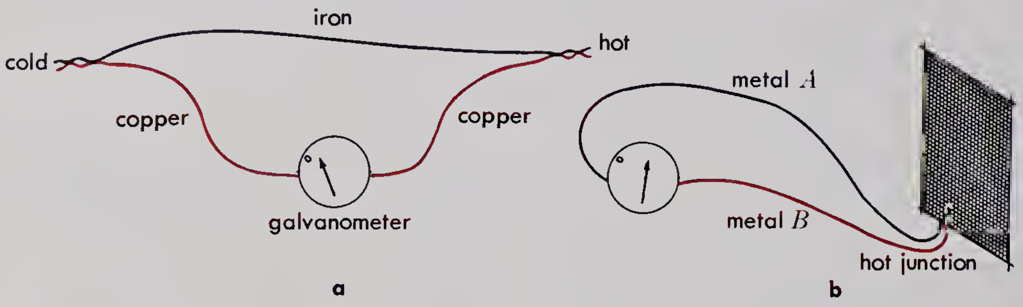
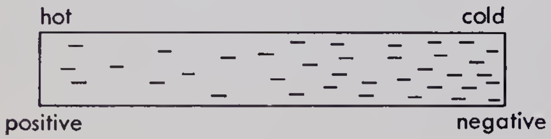


Figure 16–20 The thermocouple circuit in **a** consists of two dissimilar metals with junctions at different temperatures. From the current produced it is possible to compute the temperature difference. **b.** This diagram shows how a thermocouple can be used to measure temperatures in hard-to-get-at places — inside furnaces, living tissue, or radioactive places. Can you see where the cold junction is?

The basic theory underlying thermocouples concerns migration of free electrons or holes in conductors or semiconductors. For example, in the copper bar in Fig. 16–21, electrons are in more rapid motion at the warm end, and therefore migrate to the cold end, where there is less pronounced motion. As a result, the cold end may be a few thousandths of a volt more negative than the hot end. If semiconductors are substituted for metals, the emf generated is greatly increased. If the semiconductor is of the p-type, then holes migrate to the cool end and make it more positive than the hot end.

Figure 16–21 If one end of a metal bar is hotter than the other, free electrons tend to drift toward the cold end, making it a few microvolts more negative than the hot end.



Now consider the thermocouple of Fig. 16–22. In the top, n-type bar the cold end is more negative than the hot end; in the bottom, p-type bar the cold end is more positive than the hot end. As a result, a usable emf of about a tenth of a volt exists

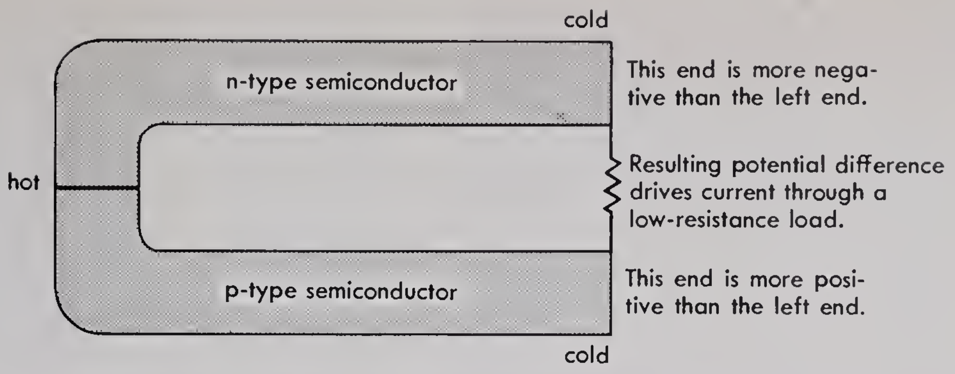

cold
n-type semiconductor
This end is more negative than the left end.
hot
Resulting potential difference drives current through a low-resistance load.
p-type semiconductor
This end is more positive than the left end.
cold

Figure 16–22 This arrangement of semiconductors produces a potential difference of perhaps a tenth of a volt between the cold ends. Many such circuits in series produce correspondingly greater potential differences.

between the two cold ends of the device. Although small, this potential difference is enough to drive useful current through a low-resistance load. If many such junctions are placed in series, the emf of each junction adds to the others, just as with series-connected electric cells.

By proper selection of n-type and p-type semiconductors for the junctions of a modern thermocouple, the efficiency of the energy conversion rises to about 10%. This efficiency can be expected to increase as scientists and engineers continue to improve semiconductor devices. Thus a thermocouple can be quite practical, particularly when it is remembered that among heat engines only large steam turbine and diesel installations exceed this efficiency. Furthermore, thermocouples need no water-filled boilers and have no moving parts. They function without noise or vibration and last almost indefinitely. Small, long-lived generators have been made using radioisotopes as the heat source, with thermocouples to convert the heat to electric energy. Some of these generators are being used in space probes and others in unmanned weather stations in arctic regions.

A thermocouple works in reverse, too. When electrons are forced through a properly prepared junction in one direction, heat is produced; when they are forced in the other direction, heat is absorbed. This makes possible some very convenient "heat pumps"; these would be particularly useful as electrically operated cooling units. Research in solid-state physics is making rapid progress along these lines, and it is expected that improved understanding of the mechanism of thermoelectricity will make for wider application of this principle.

Do It Now

If a sensitive galvanometer is available, set up a model thermocouple generator as suggested in Fig. 16–20a. Are you able to demonstrate the direct conversion of heat energy to electric energy?

16–20 Solar cells put sunlight to work. You know that when light shines on the mosaic screen in a TV camera, electrons are emitted. In a light meter used by a photographer, the behavior is similar. Here the released electrons do not escape; instead, they flow in a closed circuit and deflect the needle of a sensitive dc meter. However, until recently the emf associated with this **photoelectric effect** has been so small and the efficiency of the energy conversion so low (about 0.5%) that it was not useful as an energy source. Solid-state research has provided better materials, with efficiences of about 10%, from which useful solar cells have been made.

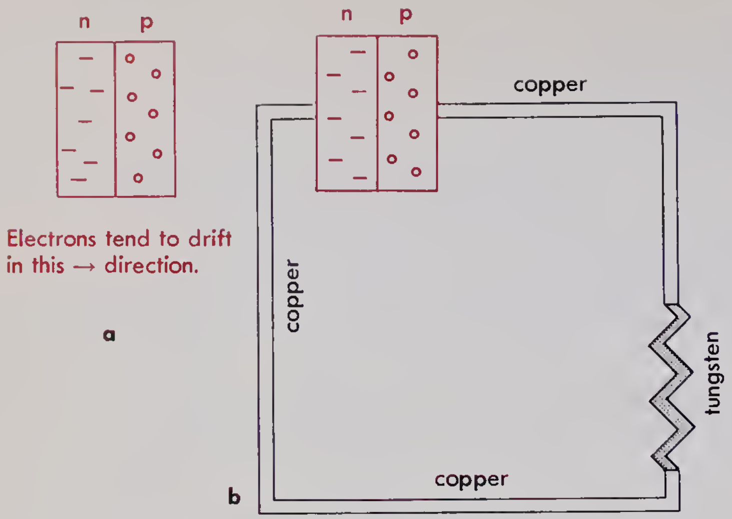


Figure 16–23 The p-n junction in **a** tends to produce an emf across itself. When connected into a complete circuit as in **b**, the junctions in the circuit provide a net emf of zero.

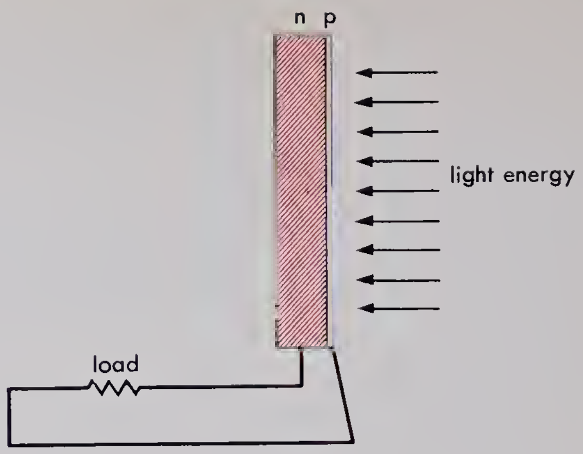


Figure 16–24 In this p-n junction, the p-layer is about 10^{-4} cm thick and is therefore transparent. Light energy strikes the junction and releases more electrons from both the p and n sections. These light-released electrons move toward the positively charged n-section, constituting an electric current. In this way, light energy is converted directly into electric energy.

To understand the operation of a **solar cell**, start with Fig. 16–23a. Here is a junction between two layers of the semiconductor silicon. One side has been doped with arsenic (n-type), the other with boron (p-type). Because of their temperature, the atoms and electrons on both sides are in motion; as a result electrons tend to drift across the junction from the n-type side, and holes tend to drift across the junction from the p-type side. The n-side becomes positive and the p-side negative. Now you might think that such an arrangement is enough to drive a current around a circuit. Figure 16–23b shows why this is not so. The circuit is a series of junctions. In addition to the p-n junction in the silicon, there is a p-silicon-copper junction, followed by a copper-tungsten junction, then a tungsten-copper junction, and finally a copper-n-silicon junction. At each junction there is an emf; some of these are in one direction, some in the opposite direction. The sum total of all these emf's is 0, so no current exists in the circuit.

Now let light shine on the silicon, as in Fig. 16–24. It shines right through the very thin p-silicon layer, and the energy of the light dislodges some electrons from the silicon on *both sides* of the junction. These are not the carrier electrons provided by the arsenic donor, but electrons that were tightly bound into the silicon crystal structure. When such an electron is dislodged, it leaves a hole behind. Now the balance in the circuit is disturbed. Since the n-side of the junction had become positive, as explained in the preceding paragraph, it attracts electrons, which travel out the wire on that side, creating a current in the circuit. Sunlight has provided energy to dislodge electrons, and to produce a current in the circuit. Modern silicon solar cells produce an emf of about 0.5 volt in bright sunlight and deliver power at the rate of about 100 watts/m^2 of exposed surface. Notice that the energy of a solar-battery circuit comes from the light that shines upon it, while the energy of a transistor circuit is supplied by dry cells or other source of emf. Solar cells have been used to power radios and the telemetering circuits of satellites and space probes.

16–21 Solid-state physics is still in its infancy. Much of today's work in solid-state is applied research — efforts to make better transistors, better solar cells, better magnets. Yet much of it is pure research — efforts to learn more just for the sake of knowledge — often without the slightest concern about possible practical applications. Sometimes these research efforts are financed by philanthropic funds or universities or government grants, because the custodians of the funds feel that such efforts in pure research will ultimately benefit mankind. Often large industries devote a part of their budget to pure research; experience shows that ultimately this policy usually brings financial rewards.

Although physicists have been exploring the microstructure of solid matter for many years, the field is still in its infancy. It promises to be one of the most important fields of physics in the future. Many questions about the structure and behavior of atoms which compose solids are unanswered. Many explanations and interpretations are incomplete; but some hypotheses appear to be at least partially correct.

Self Check

1. How can a thermocouple be used as a means of measuring temperature?
2. Why is the cold end of a conductor slightly more negative than the hot end?
3. Describe the performance of a strip of p-doped semiconductor when one end is hotter than the other.
4. What is the effect of light on a semiconductor?

Problems

Ⓐ Using the figures given for efficiency and power output of solar cells, determine the energy per m^2 available in sunlight.

Discussion Questions

If you have a p-n junction such as that in Fig. 16–23a, why would not electrons continue to flow over the junction indefinitely?

Chapter Summary

Early experiments with high-vacuum gas discharge focused physicists' attention on the cathode rays which were prominent in the discharge. It was soon learned that the cathode rays were deflected by a magnetic field. Although it was suspected that cathode rays might be a stream of charged particles, the rays did not deflect in response to an electric field. Finally this was accomplished, and J. J. Thomson discovered that the charged particles were far smaller than hydrogen ions, as well as negative. These particles were called electrons, and were shown to be moving at very high speed. Thomson worked out rather good values for the ratio of an electron's mass to its charge. Later Millikan developed the oil drop technique for measuring precisely the charge of the electron. The mass and the charge of the electron are extremely important fundamental constants.

Much modern research in particle physics is carried on with high-velocity particles which act as "bullets" and bombard materials under investigation. The bombarding particles are brought up to high speeds by accelerators. The Van de Graaff generator uses an endless belt to accumulate charges on its hollow metal sphere at potentials of the order of several million volts. A linear accelerator guides charged particles along a series of hollow sleeve-like electrodes which reverse their potential at such a rate that for a given particle, the electrode ahead is always oppositely charged. In a cyclotron, charged particles are guided in an expanding spiral path by a magnetic field, while they go back and forth between hollow dees whose electric polarity is constantly reversing. In the betatron a magnetic field keeps the electrons in a circular path, and changes in the magnetic field produce accelerating forces on the whirling electrons. In the synchrotron, changing electric fields accelerate the charged particles, while they are kept in the proper near-circular path by changing magnetic fields. As the accelerating particles approach the speed of light, part of their increased energy goes into increased mass, so the rate of electrode alternation must be decreased accordingly.

Solid-state physics is the field of study involving materials in their solid state, with particular emphasis on crystal structure, electric conductivity, and the forces which hold materials together. Semiconductor elements have four of the eight electron spaces in the outer shell filled. In pure semiconductors, these are all involved in the crystal structure, and no electrons are available to constitute an electric current. When doped with impurities which have five electrons in the outer shell, such materials have extra electrons and are n-type semiconductors. When doped with impurities which have three electrons in the outer shell, such materials have movable "holes" and are p-type semiconductors.

A junction between a p-type semiconductor and an n-type semiconductor permits electrons to flow in one direction but not in the other and hence acts as a rectifier. A transistor has several p-n junctions. When current exists across one junction, it permits current across the other, thus constituting a useful electronic device. Transistors are replacing vacuum tubes in many applications, particularly where weight and size are at a premium, and where power-handling requirements are modest. P-n junctions also play an important role in thermocouple devices and photoelectric circuits.

Vocabulary

m/e ratio (*p. 378–379*)
oil drop experiment (*p. 380–382*)
terminal velocity (*p. 380*)
particle accelerator (*p. 384*)
atom smasher (*p. 384*)
Van de Graaff generator (*p. 384*)
linear accelerator (*p. 385*)
cyclotron (*p. 386*)
dee (*p. 386*)
betatron (*p. 387*)
synchrotron (*p. 388*)
solid-state physics (*p. 389*)
semiconductor elements (*p. 389*)
electron shells (*p. 389*)
doping (*p. 390*)
donor (*p. 390*)
n-type semiconductor (*p. 390*)
hole (*p. 391*)
acceptor (*p. 392*)
p-type semiconductor (*p. 392*)
p-n junction (*p. 392*)
crystal diode (*p. 393*)
transistor (*p. 393*)
emitter (*p. 393*)
collector (*p. 393*)
base (*p. 393*)
thermocouple (*p. 396*)
photoelectric effect (*p. 397*)
solar cell (*p. 398*)

Problems

Ⓐ **1.** If the effective potential difference between the dees of a cyclotron is 100 kilovolts, what energy will an alpha particle possess after making 40 complete revolutions?

Ⓑ **2.** An electron is at rest midway between two plates 12 cm apart. With what force is it accelerated if a potential difference of 1600 V is placed across the two plates?

3. Once the electron in Problem 2 starts to move, how long will it take for it to get to the positive plate, providing it has no interference?

4. What speed will the electron in Problem 2 attain by the time it strikes the positive plate?

Discussion Questions

1. It is often said that the most modern studies of fundamental particles in physics have their roots deep in simple mechanics. Can you cite examples of this idea within this chapter?
2. Under what conditions would a falling object have no maximum or terminal velocity?

3. As the speed of a particle approaches the speed of light, its mass begins to increase measurably (see Chapter 4). When this happens, the particle moves more slowly than it would if the mass stayed the same, and it no longer covers each half-circle in the same time. Why does this fact make it impractical to use a cyclotron to accelerate electrons?
4. You have learned that sharpened metal points tend to discharge current into the air. You have also learned that Van de Graaff generators with large storage spheres can store charge at a higher potential than those with small spheres, and that they should be highly polished on their outer surface. Can you see any relation between these two statements?
5. What advantages are there in the fact that transistors are operated by power supplies of low potential difference?
6. Examine the transistors in a miniature radio or hearing aid. What advantages do they appear to have over vacuum tubes?
7. Why do transistors require no warm-up time before they are ready for operation?

Work on Your Own

1. For more information about particles, accelerators, and holes, you will find excellent articles in *Scientific American*, usually written by the scientists who have been doing the research.
2. Advertisements in *Scientific American*, *Time*, and magazines for businessmen and engineers often call attention to new products of solid-state research. List some of these and explain how they work.
3. Transistor kits from which you can build various electronic devices are available from radio supply companies and hobby shops. Some are quite inexpensive. Solar cells are also available for experimentation at school or at home.

FUNDAMENTAL UNITS

The fundamental units in this book belong to the MKSA (meter-kilogram-second-ampere) system. The definitions are stated below.

Meter	m	Length of the international meter at Sèvres, France, or (more precisely) 1,650,763.73 wavelengths in a vacuum of the orange-red light from krypton-86.
Kilogram	kg	Mass of the international kilogram at Sèvres, France.
Second	s	1/31,556,925.9747 of the solar year 1900.
Ampere	A	The constant current which, if present in each of two very long conductors one meter apart in empty space, produces on each conductor a force of exactly 2×10^{-7} newtons for each meter of length.

In countries using British units, the units are usually defined in terms of the metric units. Some of these definitions are given below.

Yard	yd	3600/3937 m, by law in the United States. 0.9144 m exactly, by international agreement among standards laboratories.
Pound	lb	0.453 592 37 kg

OTHER DEFINED VALUES AND PHYSICAL CONSTANTS

Speed of light in vacuum	c	2.997925×10^{8} m/sec
Charge of electron	e	1.60210×10^{-19} C
Coulomb of charge	C	6.2418×10^{18} electrons
Electron rest mass	m_e	9.1091×10^{-31} kg 5.48597×10^{-4} u
Proton rest mass	m_p	1.67252×10^{-27} kg 1.00727663 u
Neutron rest mass	m_n	1.67482×10^{-27} kg 1.0086654 u
Charge to mass ratio for electron	e/m_e	1.758796×10^{11} C/kg
Unified mass unit	u	1/12 the mass of an atom of the carbon-12 nuclide; 1.6604×10^{-27} kg; 931 meV
Planck's constant	h	6.6256×10^{-34} J · sec
Standard acceleration of gravity	g_n	9.80665 m/sec^2
Gravitational constant	G	6.670×10^{-11} N · m^2/kg^2
Absolute zero		−273.15°C
Mechanical equivalent of heat		4.186 J/cal; 778 ft · lb/cal
Standard atmospheric pressure	atm	760 mm of Hg; 14.7 lb/in.^{2}; 1.0325 bar
Liter	l	$1.000\,028 \times 10^{-3}$ m^3

A REVIEW OF IMPORTANT EQUATIONS

Motion, Matter, and Energy

Uniform velocity

$$v = \frac{s}{t}$$ *(p. 2)*

Average velocity

$$v_{av} = \frac{s}{t}$$ *(p. 2)*

$$v_{av} = \frac{v_1 + v_2}{2}$$ *(p. 13)*

Acceleration

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time interval}}$$ *(p. 9)*

or

$$a = \frac{v_2 - v_1}{t}$$ *(p. 10)*

or

$$a = \frac{\Delta v}{\Delta t}$$ *(p. 10)*

Centripetal acceleration (acceleration in circular motion)

$$a = \frac{v^2}{r}$$ *(p. 11)*

Displacement of a uniformly accelerated object

$$s = v_1 t + \tfrac{1}{2}at^2$$ *(p. 14)*

Newton's second law of motion

$$F = ma$$ *(p. 34)*

or

$$F = \frac{\Delta(mv)}{\Delta t}$$ *(p. 34)*

or

$$F = \frac{Wa}{g}$$ *(p. 41)*

Newton's law of universal gravitation

$$F = G\,\frac{m_1 m_2}{s^2}$$ *(p. 38)*

Weight

$$W = mg$$ *(p. 41)*

Law of conservation of momentum

total momentum before an action = total momentum after action *(p. 47)*

Centripetal force

$$\text{centripetal force} = \frac{Wv^2}{gr}$$ *(p. 49)*

Work

$$\text{work} = Fs$$ *(p. 56)*

$$\text{work} = Fs\cos\theta$$ *(p. 60)*

Power

$$P = \frac{Fs}{t}$$ *(p. 61)*

or

$$P = Fv$$ *(p. 63)*

Potential energy

$$E_p = mgh$$ *(p. 67)*

or

$$E_p = Wh$$ *(p. 67)*

Kinetic energy

$$E_k = \tfrac{1}{2}mv^2$$ *(p. 68)*

or

$$E_k = \frac{Wv^2}{2g}$$ *(p. 69)*

or

$$E_k = (m - m_o)c^2$$ *(p. 76)*

Relativistic mass

$$m = \frac{m_o}{\sqrt{1 - (v/c)^2}}$$ *(p. 74)*

Energy equivalent of mass change

$$E = \Delta mc^2$$ *(p. 77)*

Coulomb's law

$$F = k\,\frac{Q_1 Q_2}{s^2}$$ *(p. 85)*

Forces and Machines

Resultant of concurrent forces

$$\vec{R} = \sum \vec{F} \qquad (p.\ 141)$$

Equilibrium law

$$\sum F_x = 0 \qquad (p.\ 150)$$

and

$$\sum F_y = 0 \qquad (p.\ 150)$$

Moment of a force

$$M = FL \qquad (p.\ 153)$$

Law of moments

$$\sum M \text{ (clockwise)} = \sum M \text{ (counterclockwise)} \qquad (p.\ 154)$$

or

$$\sum M = 0 \qquad (p.\ 154)$$

Frictional force

$$F_f = kF_n \qquad (p.\ 171)$$

Coefficient of friction

$$k = \frac{F_f}{F_n} \qquad (p.\ 171)$$

Law of work

$$\text{work input} = \text{work output} + \text{work wasted} \qquad (p.\ 174)$$

Mechanical advantage (actual)

$$MA = \frac{F_o}{F_i} \qquad (p.\ 174)$$

Ideal mechanical advantage of an inclined plane

$$\text{ideal MA} = \frac{\text{distance along the slope}}{\text{height of the plane}} \qquad (p.\ 175)$$

Efficiency

$$\text{efficiency} = \frac{\text{useful work output}}{\text{total work input}} \qquad (p.\ 176)$$

or

$$\text{efficiency} = \frac{\text{actual MA}}{\text{ideal MA}} \qquad (p.\ 176)$$

Mechanical advantage of a lever

$$\text{MA} = \frac{\text{input arm}}{\text{output arm}} \qquad (p.\ 179)$$

Specific gravity

$$\text{specific gravity} = \frac{\text{weight of object}}{\text{weight of equal volume of water}} \qquad (p.\ 189)$$

or

$$\text{specific gravity of X} = \frac{\text{density of X}}{\text{density of water}} \qquad (p.\ 191)$$

Mass density

$$d_m = \frac{m}{V} \qquad (p.\ 190)$$

Weight density

$$d_W = \frac{W}{V} \qquad (p.\ 191)$$

Pressure

$$P = \frac{F}{A} \qquad (p.\ 191)$$

Pressure in a liquid

$$P = hd_W \qquad (p.\ 192)$$

Mechanical advantage of a hydraulic press

$$\text{Ideal MA} = \frac{\text{area of larger piston}}{\text{area of smaller piston}} \qquad (p.\ 197)$$

Archimedes' principle

$$\text{buoyant force} = \text{weight of displaced fluid} \qquad (p.\ 200)$$

Molecules and Heat Energy

Hooke's law

$$\Delta l = k\,\Delta F$$

Boyle's law

$$PV = k$$

or

$$P_1V_1 = P_2V_2$$

Conversion of temperature scales

$$F = \frac{9}{5}C + 32$$

or

$$C = \frac{5}{9}(F - 32)$$

Linear coefficient of thermal expansion

$$\alpha = \frac{\Delta l}{l\Delta t}$$

Law of Heat Exchange

heat lost = heat gained

Heat transferred

$$\Delta Q = mc\,\Delta t$$

$$\Delta Q = mL$$

Charles' law

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

General gas law

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Wave Motion

Frequency of a pendulum

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$$

Period of vibration

$$T = \frac{1}{f}$$

Equation of simple harmonic motion

$$y = r \sin \frac{360^\circ}{T} t$$

Speed of waves

$$v = f\lambda$$

Air columns and wavelength:

Column closed at one end

$$L = \frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}, \text{etc.}$$

Column open at both ends

$$L = \frac{\lambda}{2}, \frac{2\lambda}{2}, \frac{3\lambda}{2}, \text{etc.}$$

Wavelength of light from Newton's rings

$$2\,t = n\lambda$$

Wavelength of light using a diffraction grating

$$\lambda = \frac{d \sin \theta}{n}$$

Electricity and Magnetism

Law of magnets

$$F = \frac{km_1m_2}{s^2} \qquad (p.\ 217)$$

Quantity of charge

$$Q = It \qquad (p.\ 238)$$

Electric field intensity

$$E = \frac{F}{Q} \qquad (p.\ 240)$$

Potential difference

$$V = \frac{\text{Energy}}{Q} \qquad (p.\ 241)$$

Ohm's law

$$I = \frac{V}{R} \qquad (p.\ 258)$$

Potential difference across a resistor (IR drop)

$$V = IR \qquad (p.\ 261)$$

Total resistance in series

$$R_T = R_1 + R_2 + R_3 \qquad (p.\ 261)$$

Total resistance in parallel

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \qquad (p.\ 262)$$

Kirchoff's Second Rule

$$\sum \text{potential differences around a loop} = 0 \qquad (p.\ 263)$$

Power

$$P = VI \qquad (p.\ 269)$$

or

$$P = I^2R \qquad (p.\ 269)$$

or

$$P = \frac{V^2}{R} \qquad (p.\ 269)$$

Capacitance

$$C = \frac{Q}{V} \qquad (p.\ 271).$$

Force on a moving charge in a magnetic field

$$F = BQv \ \checkmark \qquad B\ \frac{N s}{C m}\ (\text{tesla}) \qquad (p.\ 280)$$

Magnetic flux

$$\Phi = BA\text{area} \qquad X \text{ in } 5/C \quad \text{Weber} \qquad (p.\ 281)$$

Force on a current across a magnetic field (motor effect)

$$F = BIl \qquad (p.\ 288)$$

Emf in a conductor moving perpendicularly across a magnetic field

$$V = Bvl \qquad (p.\ 294)$$

Generated (induced) emf

$$V = \frac{\Delta\Phi}{\Delta t} \qquad (p.\ 294)$$

Instantaneous value of alternating current

$$i = I_{\max} \sin\theta \qquad (p.\ 304)$$

Effective values of alternating current and potential difference

$$I_{\text{eff}} = 0.707\ I_{\max} \qquad (p.\ 305)$$

$$V_{\text{eff}} = 0.707\ V_{\max} \qquad (p.\ 305)$$

Capacitive reactance (sinusoidal ac)

$$X_C = \frac{1}{2\pi fC} \qquad (p.\ 309)$$

Current in a capacitive circuit

$$I = \frac{V}{X_C} \qquad (p.\ 309)$$

Induced emf in a coil

$$V = N\frac{\Delta\Phi}{\Delta t} \qquad (p.\ 311)$$

Self-inductance

$$V = L\frac{\Delta I}{\Delta t} \qquad (p.\ 311)$$

Inductive reactance (sinusoidal ac)

$$X_L = 2\pi fL \qquad (p.\ 312)$$

Current in an inductive circuit

$$I = \frac{V}{X_L} \qquad (p.\ 312)$$

Impedance in a series circuit

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \qquad (p.\ 314)$$

Current in a circuit with impedance

$$I = \frac{V}{Z} \qquad (p.\ 314)$$

Resonant frequency

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (p.\ 315)$$

Ideal transformer

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \qquad (p.\ 319)$$

and

$$V_p I_p = V_s I_s \qquad (p.\ 319)$$

Rays and Radiation

Location of image formed by a mirror or lens

$$\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{f}$$

Magnification (mirror or lens)

$$M = \frac{S_i}{S_o}$$

or

$$M = \frac{D_i}{D_o}$$

Law of illumination

$$E = \frac{I}{s^2}$$

Efficiency of a light source

$$\text{efficiency} = \frac{\text{output in lumens}}{\text{input in watts}}$$

Index of refraction

$$n = \frac{c}{v_m}$$

or

$$n \doteq \frac{v_a}{v_m}$$

Snell's law

$$n = \frac{\sin a}{\sin m}$$

Critical angle

$$n = \frac{1}{\sin c}$$

Magnifying power of a telescope

$$\text{M.P.} = \frac{\text{angular size of image}}{\text{angular size of object}}$$

Planck's quantum equation

$$E = hf$$

Kinetic energy of an emitted electron

$$E_k = hf - W$$

PERIODIC TABLE OF ELEMENTS

Values in parentheses are mass numbers of the isotopes with longest half lives

ATOMIC NUMBER
Symbol
MASS NUMBER

1 H *1.008*																	2 He *4.00*
3 Li *6.94*	4 Be *9.01*											5 B *10.8*	6 C *12.01*	7 N *14.01*	8 O *16.00*	9 F *19.0*	10 Ne *20.2*
11 Na *23.0*	12 Mg *24.3*											13 Al *27.0*	14 Si *28.1*	15 P *31.0*	16 S *32.1*	17 Cl *35.5*	18 Ar *39.9*
19 K *39.1*	20 Ca *40.1*	21 Sc *45.0*	22 Ti *47.9*	23 V *50.9*	24 Cr *52.0*	25 Mn *54.9*	26 Fe *55.8*	27 Co *58.9*	28 Ni *58.7*	29 Cu *63.5*	30 Zn *65.4*	31 Ga *69.7*	32 Ge *72.6*	33 As *74.9*	34 Se *79.0*	35 Br *79.9*	36 Kr *83.8*
37 Rb *85.5*	38 Sr *87.6*	39 Y *88.9*	40 Zr *91.2*	41 Nb *92.9*	42 Mo *95.9*	43 Tc *(99)*	44 Ru *101.1*	45 Rh *102.9*	46 Pd *106.4*	47 Ag *107.9*	48 Cd *112.4*	49 In *114.8*	50 Sn *118.7*	51 Sb *121.8*	52 Te *127.6*	53 I *126.9*	54 Xe *131.3*
55 Cs *132.9*	56 Ba *137.3*	57 71 *See* *Below*	72 Hf *178.5*	73 Ta *180.9*	74 W *183.9*	75 Re *186.2*	76 Os *190.2*	77 Ir *192.2*	78 Pt *195.1*	79 Au *197.0*	80 Hg *200.6*	81 Tl *204.4*	82 Pb *207.2*	83 Bi *209.0*	84 Po *(209)*	85 At *(210)*	86 Rn *(222)*
87 Fr *(223)*	88 Ra *(226)*	89-103 *See* *Below*															

57 La *138.9*	58 Ce *140.1*	59 Pr *140.9*	60 Nd *144.2*	61 Pm *(147)*	62 Sm *150.4*	63 Eu *152.0*	64 Gd *157.3*	65 Tb *158.9*	66 Dy *162.5*	67 Ho *164.9*	68 Er *167.3*	69 Tm *168.9*	70 Yb *173.0*	71 Lu *175.0*
89 Ac *(227)*	90 Th *232.0*	91 Pa *(231)*	92 U *238.0*	93 Np *(237)*	94 Pu *(242)*	95 Am *(243)*	96 Cm *(247)*	97 Bk *(249)*	98 Cf *(251)*	99 Es *(254)*	100 Fm *(253)*	101 Md *(256)*	102 Nb *(254)*	103 Lw *(257)*

TABLE OF NATURAL TRIGONOMETRIC FUNCTIONS

Angle	Sine	Cosine	Tangent	Angle	Sine	Cosine	Tangent
1°	.0175	.9998	.0175	**46°**	.7193	.6947	1.0355
2°	.0349	.9994	.0349	**47°**	.7314	.6820	1.0724
3°	.0523	.9986	.0524	**48°**	.7431	.6691	1.1106
4°	.0698	.9976	.0699	**49°**	.7547	.6561	1.1504
5°	.0872	.9962	.0875	**50°**	.7660	.6428	1.1918
6°	.1045	.9945	.1051	**51°**	.7771	.6293	1.2349
7°	.1219	.9925	.1228	**52°**	.7880	.6157	1.2799
8°	.1392	.9903	.1405	**53°**	.7986	.6018	1.3270
9°	.1564	.9877	.1584	**54°**	.8090	.5878	1.3764
10°	.1736	.9848	.1763	**55°**	.8192	.5736	1.4281
11°	.1908	.9816	.1944	**56°**	.8290	.5592	1.4826
12°	.2079	.9781	.2126	**57°**	.8387	.5446	1.5399
13°	.2250	.9744	.2309	**58°**	.8480	.5299	1.6003
14°	.2419	.9703	.2493	**59°**	.8572	.5150	1.6643
15°	.2588	.9659	.2679	**60°**	.8660	.5000	1.7321
16°	.2756	.9613	.2867	**61°**	.8746	.4848	1.8040
17°	.2924	.9563	.3057	**62°**	.8829	.4695	1.8807
18°	.3090	.9511	.3249	**63°**	.8910	.4540	1.9626
19°	.3256	.9455	.3443	**64°**	.8988	.4384	2.0503
20°	.3420	.9397	.3640	**65°**	.9063	.4226	2.1445
21°	.3584	.9336	.3839	**66°**	.9135	.4067	2.2460
22°	.3746	.9272	.4040	**67°**	.9205	.3907	2.3559
23°	.3907	.9205	.4245	**68°**	.9272	.3746	2.4751
24°	.4067	.9135	.4452	**69°**	.9336	.3584	2.6051
25°	.4226	.9063	.4663	**70°**	.9397	.3420	2.7475
26°	.4384	.8988	.4877	**71°**	.9455	.3256	2.9042
27°	.4540	.8910	.5095	**72°**	.9511	.3090	3.0777
28°	.4695	.8829	.5317	**73°**	.9563	.2924	3.2709
29°	.4848	.8746	.5543	**74°**	.9613	.2756	3.4874
30°	.5000	.8660	.5774	**75°**	.9659	.2588	3.7321
31°	.5150	.8572	.6009	**76°**	.9703	.2419	4.0108
32°	.5299	.8480	.6249	**77°**	.9744	.2250	4.3315
33°	.5446	.8387	.6494	**78°**	.9781	.2079	4.7046
34°	.5592	.8290	.6745	**79°**	.9816	.1908	5.1446
35°	.5736	.8192	.7002	**80°**	.9848	.1736	5.6713
36°	.5878	.8090	.7265	**81°**	.9877	.1564	6.3138
37°	.6018	.7986	.7536	**82°**	.9903	.1392	7.1154
38°	.6157	.7880	.7813	**83°**	.9925	.1219	8.1443
39°	.6293	.7771	.8098	**84°**	.9945	.1045	9.5144
40°	.6428	.7660	.8391	**85°**	.9962	.0872	11.4301
41°	.6561	.7547	.8693	**86°**	.9976	.0698	14.3007
42°	.6691	.7431	.9004	**87°**	.9986	.0523	19.0811
43°	.6820	.7314	.9325	**88°**	.9994	.0349	28.6363
44°	.6947	.7193	.9657	**89°**	.9998	.0175	57.2900
45°	.7071	.7071	1.0000	**90°**	1.0000	.0000	

REVIEW OF MATHEMATICS

This review of mathematics makes no attempt to cover all the topics in algebra and trigonometry used in this book. It does, however, give very briefly a few basic principles, and it covers in somewhat more detail those situations which many physics students find troublesome or which are treated in a special manner in the physics course.

An algebraic equation is a set of commands, telling you what operations are to be performed. For example:

$$s = v_0t + \tfrac{1}{2}at^2$$

says that to evaluate s (the distance travelled by an accelerated object), you must do the following:

1. Multiply the initial velocity (v_0) by the time (t) during which the acceleration takes place.
2. Multiply the acceleration (a) by the square of the time, and divide the product by 2.
3. Add these two terms of the equation together.

To solve an algebraic equation, you undo the operations that were used in setting up the equation. For example, suppose that you wish to solve the equation given for a. First undo the addition by using subtraction:

$$s - v_0t = v_0t + \tfrac{1}{2}at^2 - v_0t$$

Notice that the subtraction must be performed on both sides of the equation. The result is:

$$s - v_0t = \tfrac{1}{2}at^2$$

Next undo the division by using multiplication:

$$2 \times (s - v_0t) = \tfrac{1}{2}at^2 \times 2$$
$$2(s - v_0t) = at^2$$

Now undo the multiplication of a by t^2 by dividing:

$$\frac{2(s - v_0t)}{t^2} = \frac{at^2}{t^2}$$
$$\frac{2(s - v_0t)}{t^2} = a$$

In the solution just given, you did not know any particular numbers for s, v_0, t, or a. When you solve a problem in physics, you will often find it helpful to solve the basic equation before putting in the numbers, but that is not necessary. For example, the equation for the area of a circle is $A = \pi r^2$. Suppose you want to know the radius of a circle with an area of 100 cm². You can write it this way:

$$100\ \text{cm}^2 = \pi r^2$$

Undo the multiplication of r^2 by dividing by π:

$$\frac{100\ \text{cm}^2}{\pi} = \frac{\pi r^2}{\pi}$$
$$31.8\ \text{cm}^2 = r^2$$

Undo the squaring by taking the square root:

$$\sqrt{31.8\ \text{cm}^2} = \sqrt{r^2}$$
$$5.64\ \text{cm} = r$$

Notice that the square root of cm² is cm. Throughout the book you will be expected to write in the units and to treat them in the same way that you do the letters. (*See pp.* 2–3).

Addition of fractions is necessary in some problems in physics. For example, the equation describing the behavior of a lens is:

$$\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{f}$$

If an object is placed at a distance D_o from a lens with a focal length of f, the image will be formed at a distance D_i from the lens. Suppose that you have placed an object 3.0 m from the lens and find that the image is formed 2.0 m from the lens. You wish to find f. Substituting:

$$\frac{1}{3.0\text{ m}} + \frac{1}{2.0\text{ m}} = \frac{1}{f}$$

Now multiply both right and left members of the equation by 6.0 m common denominator.

$$(6.0\text{m})\frac{1}{3.0\text{ m}} + (6.0\text{m})\frac{1}{2.0\text{ m}} = \frac{1}{f}(6.0\text{m})$$

$$2.0 + 3.0 = \frac{6.0\text{m}}{f}$$

$$5.0 = \frac{6.0\text{m}}{f}$$

Undo the division by multiplying by f

$$(f)\ 5.0 = \frac{6.0\text{m}}{f}(f)$$

$$5.0f = 6.0\text{m}$$

Undo the multiplication by dividing by 5.0

$$\frac{5.0f}{5.0} = \frac{6.0\text{ m}}{5.0}$$

$$f = 1.2\text{ m}$$

The steps can be shortened when you are skilled in the "undoing" method for solving equations. For example, the equation for finding the total resistance of three resistors in parallel in an electric circuit is:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Suppose that you wish to have a total resistance of 20 ohms (Ω), and you have two resistors of 50 Ω and 100 Ω. You wish to know the required size of the third resistor.

The solution is:

$$\frac{1}{20\ \Omega} = \frac{1}{50\ \Omega} + \frac{1}{100\ \Omega} + \frac{1}{R_3}$$

$$\frac{1}{20\ \Omega} - \frac{1}{50\ \Omega} - \frac{1}{100\ \Omega} = \frac{1}{R_3}$$

$$5.0 - 2.0 - 1.0 = \frac{100\ \Omega}{R_3}$$

$$2.0 = \frac{100\ \Omega}{R_3}$$

$$R_3 = \frac{100\ \Omega}{2.0}$$

$$R_3 = 50\ \Omega$$

Practice problems

1. $F = ma$ $\quad m = 10, F = 80, a = ?$
2. $F = \frac{Wa}{g}$ $\quad F = 4, W = 64, g = 32, a = ?$
3. $C = \frac{5}{9}(F - 32)$ $\quad C = 20, F = ?$
4. $F = \frac{mv^2}{r}$ $\quad v = 40, F = 80, m = 10, r = ?$
5. $E = \frac{1}{2}mv^2$ $\quad E = 125, m = 10, v = ?$
6. $\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{f}$ $\quad f = 50, D_o = 80, D_i = ?$
7. $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$ $\quad R_1 = 20, R_2 = 30, R_3 = 40, R_T = ?$

An exponent tells how many times another number, called the base, is to be used as a factor. Examples:

$$2^5 = 2 \cdot 2 \cdot 2 \cdot 2 \cdot 2 \qquad a^3 = a \cdot a \cdot a$$

The meaning of negative, zero, and fractional exponents is given by these relationships:

$$a^{-n} = \frac{1}{a_n} \qquad a^0 = 1 \text{ (for all values of a)}$$

$$a^{1/n} = \sqrt[n]{a}$$

Rules for combining exponential expressions are:

$$a^m a^n = a^{m+n}$$

$$(a^m)^n = a^{mn} \qquad (ab)^m = a^m b^m$$

$$\frac{a^m}{a^n} = a^{m-n} \qquad \left(\frac{a}{b}\right)^m = \frac{a^m}{b^m}$$

Scientific notation simplifies the writing of numbers by using powers of 10. For example:

$$1000 = 10 \cdot 10 \cdot 10 = 10^3$$

$$1{,}000{,}000{,}000{,}000{,}000 = 10^{15}$$

Now suppose you wish to write 6,147,300,000 in this way. You could write:

$$61{,}473 \times 100{,}000 = 61{,}473 \times 10^5$$

or

$$6.1473 \times 1{,}000{,}000{,}000 = 6.1473 \times 10^9$$

Notice that the exponent 5, in the first case, is the number of places that the decimal point was moved to the *left* in 6,147,300,000 to arrive at 61,473. Similarly, the decimal point was moved 9 places to the left in the second case. Both of these ways of writing the large number are correct, but the second form is usually preferred.

Very small numbers can be handled similarly:

$$0.00043278 = \frac{4.3278}{10000}$$

$$= \frac{4.3278}{10^4} = 4.3278 \times 10^{-4}$$

Here the exponent equals the number of places the decimal point was moved to the *right*.

Try performing the following operations:

$$\frac{6{,}130{,}000{,}000{,}000 \times 0.000000374 \times 45}{2{,}700{,}000{,}000 \times 0.00000000034 \times 2300} = ?$$

First, simplify by writing each factor in scientific notation.

$$\frac{6.13 \times 10^{12} \times 3.74 \times 10^{-7} \times 4.5 \times 10^{1}}{2.7 \times 10^{9} \times 3.4 \times 10^{-10} \times 2.3 \times 10^{3}} = ?$$

Now gather like factors and combine.

$$\frac{6.13 \times 3.74 \times 4.5 \times 10^{12} \times 10^{-7} \times 10^{1}}{2.7 \times 3.4 \times 2.3 \times 10^{9} \times 10^{-10} \times 10^{3}}$$

$$= \frac{6.13 \times 3.74 \times 4.5 \times 10^{4}}{2.7 \times 3.4 \times 2.3}$$

In this way there is no wasted effort, and the arithmetic is much simpler. You may, of course, use either slide rule or logarithms when you have reduced the expression to the last step.

Practice problems

1. Simplify each of the following:

(a) a^2a^3 (b) $\frac{a^3}{a^2}$ (c) $\frac{a^2}{a^3}$

(d) $\frac{a^3b^2c^5}{ab^4c^2}$

(e) $2 \times 10^2 \times 6 \times 10^{-3} \times 3 \times 10^4$

(f) $\frac{3 \times 10^2 \times 14 \times 10^3}{7 \times 10^4 \times 10^5}$

2. Write in scientific notation:

(a) 141,000 (b) 0.073
(c) 0.00013500 (d) 48,160,000,000
(e) 2,000,000 (f) 0.015903

3. Set up in scientific notation and solve:

(a) A light year is 186,000 × 3600 × 24 × 365 miles

(b) The number of wavelengths of red light in 1 inch is

$$\frac{1}{0.00000065 \times 39.37}$$

(c) The wavelength of a station broadcasting at 1340 kilocycles is

$$\frac{300{,}000{,}000}{1{,}340{,}000} \text{ meters}$$

Percent of error in a measurement is defined as:

$$\frac{\text{measured value} - \text{correct value}}{\text{correct value}} \times 100$$

The "correct value" may be the value considered by experts to be the best measurement that has been made. The Physical Constants given in the Appendix are such "best" values.

In some cases (when you are using a meter stick) the correct value is considered to be a distance marked on the stick, and you estimate the maximum possible error you might make when you use the stick. If the stick is marked in mm, you might think that the maximum possible error is 0.5 mm. Then you estimate the per cent of error as:

$$\frac{\text{estimated maximum error}}{\text{correct value}} \times 100$$

In the case of the meter stick, if you are measuring something that is 1 m long (1000 mm), the estimated per cent of error is:

$$\frac{0.5\text{ mm}}{1000\text{mm}} \times 100 = 0.05\%$$

However, if you are measuring something that is 1 cm long (10 mm), the estimated per cent of error is:

$$\frac{0.5\text{ mm}}{10\text{ mm}} \times 100 = 5\%$$

Often you have no "best" value for comparison when you make measurements in the laboratory. If you have made two measurements of the same quantity, you may wish to calculate the per cent of difference between them. In that case, you use the formula:

$$\text{percent of difference} = \frac{\text{difference between the measurements}}{\text{average of the measurements}} \times 100$$

Practice problems

1. The speed of light is measured by a student as 2.8×10^8 m/sec. What is his per cent of error?
2. Millikan, who first measured the charge on the electron, reported a value of 1.59×10^{-19}. It was later found that this was incorrect because of an error in one of the constants, measured by other people, which he had used in his calculations. What was the per cent of error?
3. If you estimate a maximum possible error of 0.5 g when you use a certain balance for weighing, what is the per cent of error when the object has a weight of (a) 2 kg? (b) 800 g? (c) 20 g?
4. Two measurements of the index of refraction of a piece of glass are 1.543 and 1.598. What is the per cent of difference?

Trigonometry of the right triangle involves several functions, among them the sine, cosine, and tangent, defined below:

$$\text{sine of an angle} = \frac{\text{side opposite the angle}}{\text{hypotenuse}}$$

$$\text{cosine of an angle} = \frac{\text{side adjacent to the angle}}{\text{hypotenuse}}$$

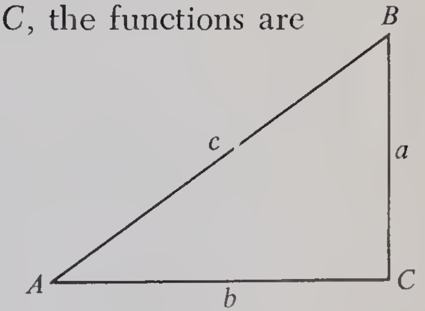
$$\text{tangent of an angle} = \frac{\text{side opposite the angle}}{\text{side adjacent to the angle}}$$

In the triangle *ABC*, the functions are

$$\sin A = \frac{a}{c}$$

$$\cos A = \frac{b}{c}$$

$$\tan A = \frac{a}{b}$$



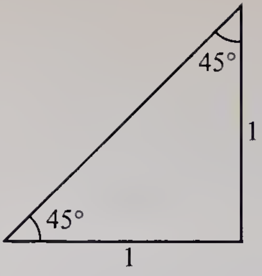
In addition to the trigonometric functions, the Pythagorean theorem is also useful in problems dealing with the right triangle.

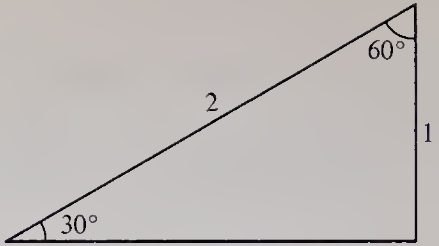
In terms of the triangle shown on page 673, the theorem is:

$$c^2 = a^2 + b^2$$

Practice problems

1. Write formulas for the three functions of angle B in the diagram above.
2. Use the Pythagorean theorem and the diagrams shown here to calculate the functions of angles of 30°, 45°, and 60°.





3. In the right triangle ABC, angle A is 25° and side a is 40 ft. Find sides b and c.
4. In the right triangle ABC, a is 50 cm and b is 40 cm. Find c and angles A and B.

THE GREEK ALPHABET

Capital	Lower case	Name	Capital	Lower case	Name
Α	α	alpha	Ν	ν	nu
Β	β	beta	Ξ	ξ	xi
Γ	γ	gamma	Ο	ο	omicron
Δ	δ	delta	Π	π	pi
Ε	ϵ	epsilon	Ρ	ρ	rho
Ζ	ζ	zeta	Σ	σ or ς	sigma
Η	η	eta	Τ	τ	tau
Θ	θ	theta	Υ	υ	upsilon
Ι	ι	iota	Φ	ϕ	phi
Κ	κ	kappa	Χ	χ	chi
Λ	λ	lambda	Ψ	ψ	psi
Μ	μ	mu	Ω	ω	omega

TABLE OF PREFIXES

The following prefixes are used to indicate decimal fractions or multiples of units in the metric system.

FRACTIONS			MULTIPLES		
Prefix	Value	Symbol	Prefix	Value	Symbol
deci	10^{-1}	d			
centi	10^{-2}	c	kilo	10^{3}	k
milli	10^{-3}	m	mega	10^{6}	M
micro	10^{-6}	μ	giga	10^{9}	G
nano	10^{-9}	n	tera	10^{12}	T
pico	10^{-12}	p			

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Numerals in **boldface** refer to pages on which important terms are introduced or defined; numerals in *italics* refer to pages containing an illustration without related text.

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INVESTIGATION

1

How a Scientist Learns

Introduction

What is a scientist? From comic books and science fiction movies you might think he is a sort of magician, one who performs strange tricks. While many scientists enjoy putting on a show with some of their equipment, this is far from being their real purpose.

A scientist is inquisitive. He wonders what kind of world this is, what kinds of things there are in it, how they behave, and whether there are any basic rules of behavior. His real purpose is to satisfy his curiosity, to seek for an understanding of natural phenomena. Frequently he seeks also to apply his understanding in useful ways.

Everyone can be a scientist. Of course not everyone wants to earn his living in this way, but every person can be curious, can seek to understand the world about him, can collect information, and can try to interpret what he learns. The difference between a scientific person and an unscientific one is that the scientific person collects his information more carefully and more thoroughly, and is more cautious in drawing conclusions.

The purpose of this investigation is to introduce you to the way in which a scientist learns.

Equipment

Small block of wood; small wheeled cart; metal ball that can be suspended; support for suspension; string; heavy metal ball weighing more than the cart.

Procedure

A scientist often starts with a question. In the investigation you are about to start, the question is: How do things move? If you were an experienced scientist, such a question is all that you would need to start you on an investigation. Since you are not an experienced scientist, some of the possible steps in the investigation will be pointed out to you.

There are many ways to approach a scientific problem, and no two scientists are likely to do it in exactly the same way. You might start your study of motion by collecting all the facts you can about moving objects, and by trying to organize the facts so that they make sense. In a way, you have been doing this all your life, so that already you know a lot about motion. Therefore you are in a position to use what you already know to make a guess about the answer to the question: How do things move? Your guess is called a *hypothesis.* It might be:

Hypothesis: Objects move when they are pushed or pulled.

Maybe this hypothesis is true; maybe it is not true. You must now test the hypothesis in order to find out whether or not it is a good one.

STEP 1 Place a smooth block of wood on the laboratory table and give it a sharp push with your hand, but do not keep your hand on the block. Does the block move only while your hand is touching it, or does it continue to move after your hand stops pushing? What happens to the speed of the block after you stop pushing?

As a result of this investigation, you would probably wish to revise the hypothesis, perhaps like this:

Revised Hypothesis: Objects move when they are pushed or pulled, and slow down when the force is removed.

STEP 2 Next investigate the matter of slowing down. Will an object always slow down in the same way when you give it the same push at the start? Put the small wheeled cart on the floor and give it a push. Measure how far it goes before it stops. Then turn it upside down so that the wheels are in the air. Push again, with what seems to be the same force, and again measure how far it goes before it stops. Was the path of the cart straight or curved?

This part of the investigation was not very exact because you cannot be sure that you you used the same force each time. Therefore, repeat the investigation as indicated below.

STEP 3 Suspend a metal ball by a string from an overhead support, as shown in Fig. 1–1. When the ball is hanging motionless, place the cart so that it just touches the ball. Then pull the ball back a short distance, keeping the string taut. Place some object behind the ball so that you can locate the spot again. Let the ball go, and measure the distance traveled by the cart. Turn the cart over and repeat. Measure for 3 trials and average the measurements. In your *Data Book* record the data for each case in a chart like the one at the right. Be sure to note in the parentheses the unit of measurement (in., cm, etc). Was the path of the cart straight or curved?

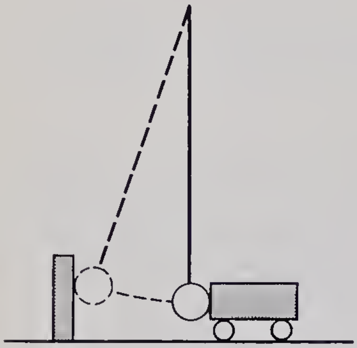


Fig. 1–1 Suspended metal ball.

Distances traveled by cart with wheels down

Trial 1 __________

Trial 2 __________

Trial 3 __________

Sum __________

Average __________

As you will learn later in your physics course, by letting the ball swing from the same height, you gave the same amount of energy to the cart each time. As a result of the push, the cart moved. In both cases the cart slowed when the pushing force was removed. So far the hypotheses seems good.

However, the slowing rate was not the same in both cases, although the same object, the cart, was used both times, and it received the same energy both times. The only difference was that in one case the cart rolled on its wheels, and in the other case it slid upside down. The difference in the slowing rate must, therefore, have something to do with the contact between the cart and the floor. The floor must provide resistance to the motion of the cart, and the resistance must be less when the wheels are used.

You are familiar with frictional resistance of this sort from past experiences. Try to push a heavy piece of furniture across the room. Where the furniture touches the floor, a force seems to push back on the furniture. If the legs have castors, the force pushing back is less.

A sizeable and noticeable force operates against you when you pull a sled on bare pavement, pedal a bicycle through sand, or try to turn a key in a rusty lock.

The hypothesis needs further revision to take the force of friction into account:

> *Second Revised Hypothesis: Objects move when they are pushed or pulled, and slow down when the force is removed. They come to rest sooner when there is friction than when there is no friction.*

STEP 4 This hypothesis must be tested, particularly the part about "no friction." How can you tell when there is no friction? Was there friction when the cart rolled on its wheels? The best way to check this is to see whether you can find another object having the same weight as the cart, that will travel farther when it receives the same amount of energy. Try a heavy, steel ball. Therefore, repeat Step 3, this time using the heavy, steel ball as one object, and the wheeled cart as the other object. Before you start, weigh the steel ball, and add weights to the cart until it weighs the same as the ball. Record your measurement in your *Data Book* by a chart similar to the one for Step 3. Do the cart and ball travel in straight or in curved paths?

Discussion

Refer to your data when answering these questions.

1. Was there a frictional force when the cart was running on its wheels? How do you know?
2. Is it possible that frictional force acted on the rolling ball? Give reasons for your answer.
3. As the force of friction became smaller, what happened to the distance traveled by the moving objects? If the force of friction could be reduced to zero, and if no other outside force were acting on a moving object, what would happen? Questions like this last one are sometimes called "thought experiments." You cannot actually set up a situation in which the friction is zero, but you have investigated situations with decreasing amounts of friction. Therefore, in the thought experiment you go beyond these real situations and say what you think would be most likely if there were no friction at all.
4. Write a revised hypothesis reflecting your findings in this investigation. Include your observations about the shape of the path.
5. Instead of setting up a new investigation to test your new hypothesis, use the following common experiences to test it: **a)** You are in a moving car and the brakes are suddenly applied. In what direction are you jerked? Tell how this observation supports or disagrees with your hypothesis. **b)** You are in a car that speeds up suddenly. In what direction are you jerked? Tell how this supports or disagrees with your hypothesis.
6. Another way to test a hypothesis is to predict what ought to happen if the hypothesis is true, and then see whether the prediction turns out to be correct. Suppose you have a ball attached to a string, and that you hold the string at one end and make the ball move in a circle on a table top, as shown in Fig. 1–2. When the ball is in the position shown in the diagram, you let go of the string. If your hypothesis is a good one, in what direction should the ball now move? Show your answer by copying Fig. 1–2 and indicating the predicted direction with an arrow. Check the prediction by performing the experiment. Does the result agree with the prediction?

7. Discuss the methods used in this investigation, answering such questions as: **a)** Why is it useful to have a hypothesis? **b)** Why was the method of Step 3 better than that of Step 2? **c)** Why is it better to make 3 trials and take an average, rather than to make only 1 trial each time? **d)** How did the various parts of the investigation make it possible for you to discuss the "thought experiment"? **e)** How is a hypothesis tested?

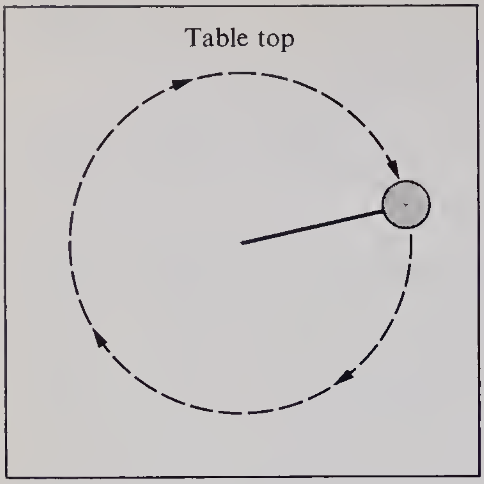


Fig. 1–2 Looking down on a revolving metal ball.

INVESTIGATION 2

The Measurement of Length

Introduction

Investigation 1 required you to make measurements. However, the difference in distance traveled by the various objects was so great that very careful measurement was not required. Often you will need to make measurements more carefully than in the first investigation. The purposes of Investigation 2 are: **a)** to teach you some of the ways in which measurements can be made as accurately as possible, and **b)** to help you to learn about the metric units of length and why this system is preferred by scientists.

In this investigation you will use a meter stick to measure the length and width of your laboratory table, first in centimeters (cm) and then in inches (in.). You will learn rules for making the measurement as accurately as possible. Using your measurements, you will calculate the area of the table to the proper number of significant digits.

Equipment

Meter stick (centimeters on one side and inches on the other); flat block of wood (see Fig. 2–1); laboratory table.

A. RULES FOR MAKING ACCURATE MEASUREMENTS WITH A MEASURING STICK

This part of the investigation can be done at home, using a yard stick or foot rule.

Procedure

RULE 1 Try to begin exactly at one end of the distance being measured. This is not always as easy as it appears. When measuring the length of a table, for example, it is sometimes difficult to begin the measurement exactly at the edge. This is especially true when the table edge is rounded. Figure 2–1 illustrates a simple technique for meeting this difficulty.

Without using an end block, try to measure the length or width of a desk top, a chair, or other object with an irregular edge. Then, using an end block, note how much easier measurement is with the technique illustrated in Fig. 2–1. Record the measurement in your *Data Book.*

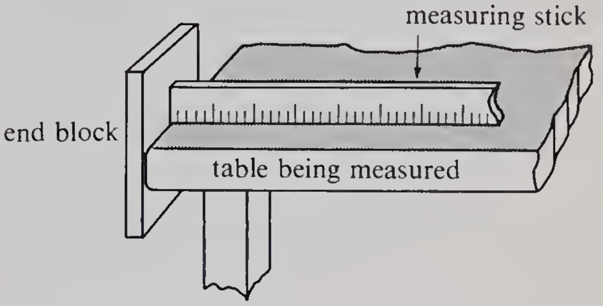


Fig. 2–1 Using an end block for accuracy.

RULE 2 Avoid parallax. Figure 2–2 illustrates the possibility of misreading a measuring stick if your eye is in the wrong position. Here a meter stick is being observed by three different people, with their eyes at A, B, and C, respectively. There are two ways to avoid this error, called **parallax**. One is to make all readings from the proper angle, usually 90 degrees. The other is to place the mark on the measuring stick as close as possible to the object being measured, as illustrated in Fig. 2–3.

Fig. 2–2 The eye directly above the measuring stick at B sees the correct reading, 25 cm. The eye at A sees 24.6 cm, while the eye at C sees 25.4 cm.

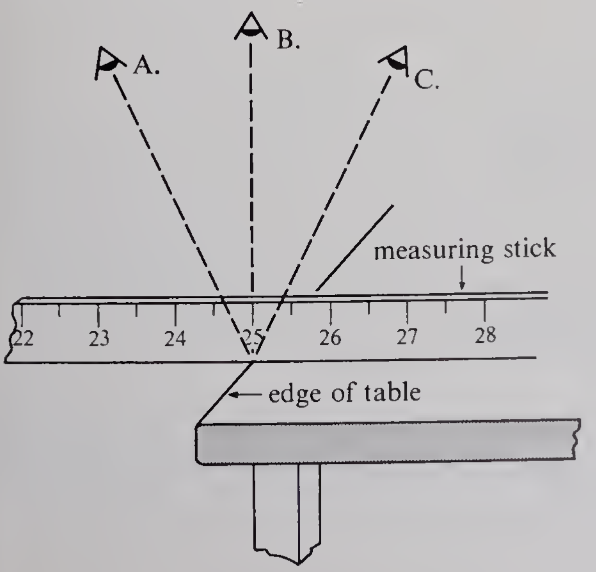
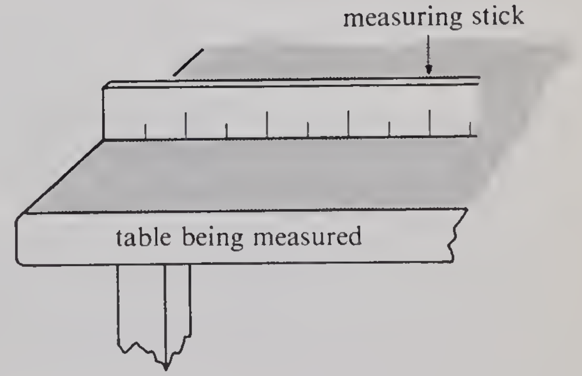


Fig. 2–3 Divisions on the measuring stick are placed next to the object that is being measured.



RULE 3 Record all of the digits of which you are certain, plus one that you estimate. If the edge of a length you are measuring falls, as shown in Fig. 2–4a, you would record the length as 11.7 cm or 11.6 cm, knowing that you are guessing the last digit. The digit that you guess is called a doubtful digit.

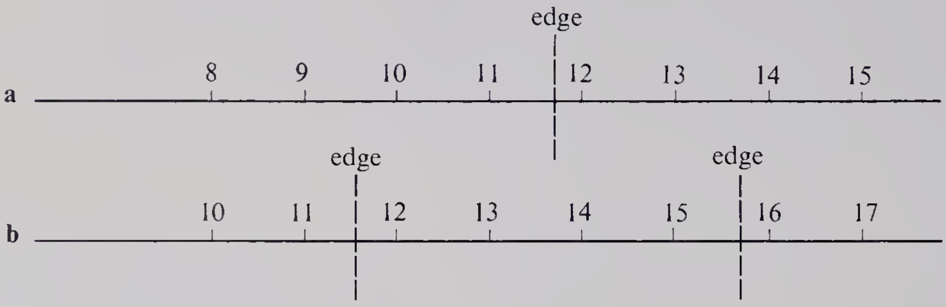


Fig. 2–4 Estimate the last digit in a measurement.

Record in your *Data Book* the lengths shown in Fig. 2–4b. Circle the doubtful digit in your answer.

RULE 4 Apply a zero correction when necessary. If the end of a ruler is worn or broken, the zero point may be missing. When there is any doubt about the correctness of the zero point, you should set some mark other than zero at one end of the object to be measured. In Fig. 2–5 the 10-cm mark is set at the edge of the table. Since the other edge is at the 70-cm mark, you know that the distance measured is 70 cm minus 10 cm, or 60 cm.

Measure the same distance you measured in Rule 1, but without using the end of the ruler. Record your result.

Note that you cannot use the end block as in Fig. 2–1 if you find it necessary to use a zero correction. See Discussion Question 2.

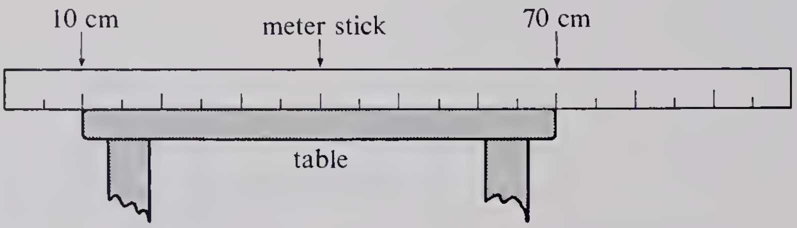
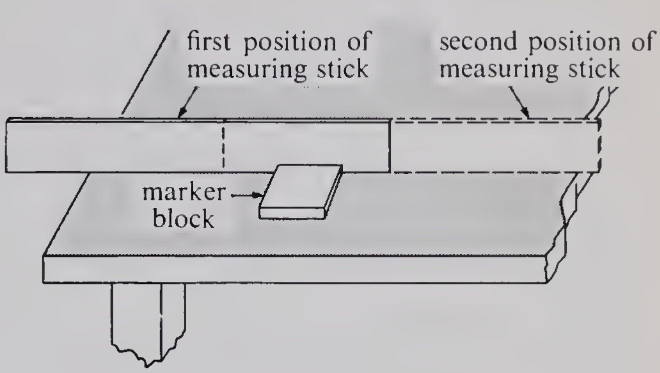


Fig. 2–5 The use of the zero-correcting technique avoids end error of the measuring stick.

RULE 5 Make measurements in the proper direction. To measure height, you should measure in a vertical direction. To measure the distance between lines or planes, you should place the measuring stick perpendicular to them.

RULE 6 Use care in measuring distances greater than the length of the measuring stick. You often need to measure distances greater than the length of the measuring stick. In such a case people often lay the stick along the distance to be measured, mark the position of one end, and then move the measuring stick so that the zero end corresponds with the mark. The width of the mark may introduce error. This may be avoided by using the edge of a block for the mark, as suggested in Fig. 2–6. Figure 2–6 also shows how to avoid using the worn ends of the measuring stick.

Fig. 2–6 A marker block can be used when the distance is longer than the measuring stick. The marker block might be placed with its left end at the 80-cm mark, for example. Then the measuring stick might be moved until its 20-cm mark is at the left end of the marker block.


first position of measuring stick
second position of measuring stick
marker block

RULE 7 Average several measurements for greater accuracy. If you measure the width of a table, there are two important possible sources of error. You may make a mistake in the measurement, and the table may not be the same width at all places. You can improve your results by measuring the width at several places. If you have made a mistake, it will show up by comparison with the other measurements. For example, suppose that you have made the following record:

Observation	Width of table (cm)
1	44.73
2	44.91
3	45.10
4	45.96
5	45.08

One of these observations is probably due to a mistake made by the observer. The differences in the other measurements are probably due to irregularity in the table and to unavoidable errors of observation. When these results are averaged, such errors and irregularities tend to cancel out. Therefore the average is more representative of the true width of the table than is an individual measurement. Ignore the observation that is a mistake, and find the average of the others.

Discussion

1. When you use an end block, what should be the angle between its surface and the measuring stick? How can you be sure that it makes the proper angle?

2. If a measuring stick is longer than the object being measured, how could you place the end block where the stick extends beyond the end of the object? Show with a sketch or describe in words.
3. Compare the measurement you made in Rule 1 with that of Rule 4. If there was a difference, in which measurement would you have greater confidence? Why?
4. Describe measuring situations in which it would be impossible to avoid using the end of the measuring stick.
5. When you wish to measure the height of a table top above the floor, how can you be sure the measurement is vertical?

B. USE THE RULES OF MEASUREMENT TO DETERMINE THE DIMENSIONS OF A TABLE

Procedure

Before you start your investigation, read Appendix 1, *Scientific Notation;* Appendix 2, *Significant Digits;* and Appendix 5, *The Metric System.* Do the practice problems of Appendix 1 and 2 and have your answers checked.

STEP 1 Measure the length and width of your table in centimeters to the nearest 0.01 cm and in inches to the nearest 1/16 in. Make each measurement at least five times. Record all of your measurements in a neat chart in your *Data Book.* Cross out any that are obvious mistakes. Determine the average value of each measurement.

STEP 2 Convert the average width obtained in Step 1 to **a)** millimeters (mm); **b)** meters (m); **c)** sixteenths of an inch.

STEP 3 Calculate the area of the table in cm^2 and in $\mathrm{in.}^2$, taking into account the correct number of significant digits. Record the result in scientific notation.

STEP 4 Convert the table area from cm^2 to m^2 and to mm^2; and from $\mathrm{in.}^2$ to ft^2.

Discussion

1. What are some of the advantages of the metric system of measurement?
2. Some people say that the metric system of measurement is preferred by scientists because it is more accurate. Do you agree? Why?

INVESTIGATION

3

The Slide Rule

Introduction

In a physics course you should learn physics, not arithmetic. However, it often seems to many students that they spend three hours multiplying and dividing for every hour they spend learning something new. The three hours can be cut to a fraction of an hour if you learn to use the slide rule.

The slide rule is a calculating machine that multiplies, divides, squares, and takes square roots. The slide rule will not add or subtract numbers. Some slide rules will perform other operations (finding, for example, the value of $17^{1.2}$), but you will be concerned with the simpler operations.

Equipment

Slide rule with A, B, C, and D scales.

Procedure

STEP 1 To locate a number on the slide rule: Examine the scale marked D on your slide rule. You will see that it is numbered from left to right in large numbers: 1, 2, 3, 4, 5, 6, 7, 8, 9, 1. Suppose that you want to locate the number 4.3. It will lie between 4 and 5, as shown in Fig. 3–1a. Since the slide rule has no decimal point, the same setting stands for 4.3, 43, 430, 4,300,000 and 0.0043. Whenever you locate a number, place the indicator hair line directly over it.

If you wish to locate 4.32 (or 4320 or 0.432), move the hair line to the right by the proper amount. This involves estimating the proper position, as shown in Fig. 3–1b.

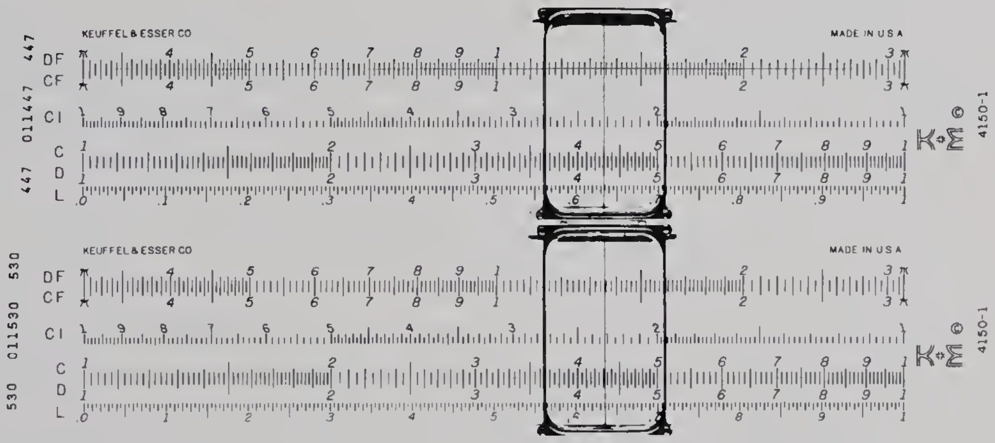


Fig. 3–1 The location of numbers on the slide rule. The location of 4.3 is shown in **a**; that of 4.32, in **b**.

Locate each of the following points and then check your setting with that shown below in Fig. 3–2: 84.7; 6980; 504; 32.2; 0.0275; 2.03; 116; 0.0975; 107.2; 10.8.

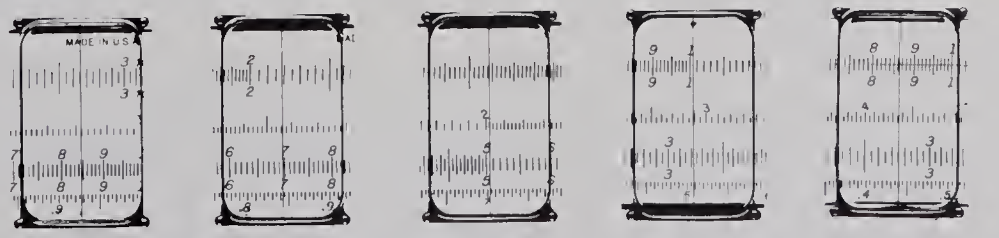


Fig. 3–2

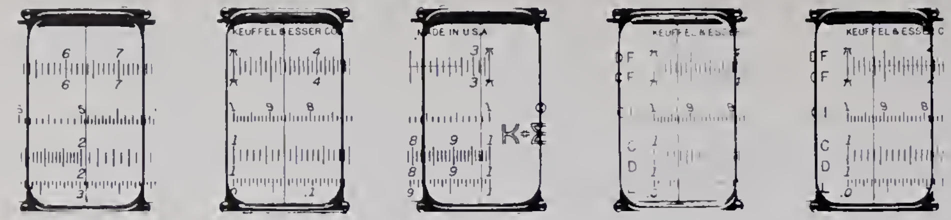


Fig. 3–2 (cont.) Location of numbers listed in Step 1.

STEP 2 To multiply (*C* and *D* scales): Suppose you wish to multiply 17.9 × 3.49. Use the following method:

a) Locate the first number (17.9) on the *D* scale, using the hair line.
b) Without moving the hair line, move the *C* scale until the 1 of that scale is directly below the hair line.
c) Without moving the *C* scale, move the hair line until it is directly over the second number (3.49) on the *C* scale.
d) Read the answer below the hair line on the *D* scale. If you have done this correctly, your answer is 625. However, you do not know where the decimal point belongs.
e) Locate the decimal point by simplifying the problem. Call it 20 × 3. The answer is 60. Therefore, the answer obtained by slide rule must be 62.5.

If you had multiplied 17.9 × 3.49 by hand, your answer would be 62.471. The slide rule gives you the answer rounded off to 3 digits. If the number starts with 1 (16.31, for example), you can locate 4 digits on the slide rule.

Multiply the digits below and check your answers. You will find that in some cases your second number on the *C* scale is out in space. When this happens, just use the 1 at the other end of the *C* scale as in **b**) above. In the *C* group of problems do not record the result you obtain when you multiply the first two numbers together (15 × 42, for example). Instead, set the 1 of the *C* scale beside that result, and then proceed to multiply by the third number.

A. 12 × 36
42 × 2.3
1.79 × 36
49.5 × 0.0194

B. 98 × 21.2
0.063 × 462
47.3 × 36
0.00076 × 0.034

C. 15 × 42 × 6.3
8.2 × 5.2 × 12
41 × 0.03 × 0.4

STEP 3 To divide (*C* and *D* scales): In physics problems, division is usually indicated by the line of a fraction: $\frac{5.73}{147.2}$

a) With the hair line, locate the numerator (5.73) on the *D* scale.
b) Without moving the hair line, move the *C* scale until the denominator (147.2) is directly below the hairline.
c) Without moving the *C* scale, move the hair line to the 1 of the *C* scale.
d) Read the answer on the *D* scale below the hair line. It is 389, with no regard for the decimal point.

e) Again simplify the problem to locate the decimal point: $\frac{5}{100} = 0.05$. Therefore the answer is 0.0389.

Perform the following divisions and check the answers:

$$\frac{34}{62} \qquad \frac{34}{19} \qquad \frac{0.645}{6.21}$$

STEP 4 Combinations of multiplication and division (*C* and *D* scales): A problem like $\frac{2.7 \times 0.0043}{39.1}$ can be done by multiplying 2.7 by 0.0043 and then dividing the answer by 39.1. Another way is to divide 2.7 by 39.1 and then multiply by 0.0043. You will get the same answer either way (0.000297), but it takes fewer steps to divide first and then multiply. It is not necessary to write down the answer to the first operation. Simply capture the answer with the hair line and proceed with the next step. Try the following combinations of division and multiplication.

$$\frac{32 \times 0.29}{2.08} \qquad \frac{5.02 \times 1.735}{0.858} \qquad \frac{0.0322 \times 1.07}{7.08}$$

STEP 5 To locate the decimal point by use of scientific notation: Read Appendix 1, *Scientific Notation*, if you do not know what this means. In a problem like those of the preceding paragraph, it is often easier to locate the decimal point by expressing all of the quantities in scientific notation:

$$\frac{2.7 \times 0.0043}{39.1} = \frac{2.7 \times 4.3 \times 10^{-3}}{3.91 \times 10^{1}}$$

In simplified form, this becomes:

$$\frac{3 \times 4 \times 10^{-3}}{4 \times 10^{1}} = 3 \times 10^{-4} \qquad \text{or} \qquad 0.0003$$

Thus when the slide rule gives you 297, you know it should be 2.97×10^{-4} or 0.000297.

STEP 6 How the slide rule is constructed: The distances marked on the *C* and *D* scales of your slide rule are proportional to the logarithms of the numbers printed on the scale. To check this statement, compare the *D* and *L* scales. The *L* scale is an ordinary scale marked in inches and decimal parts of an inch. Therefore if you locate a number on the *D* scale with the hair line, you will find its logarithm to the base 10 on the *L* scale below the hair line. When you multiply with the slide rule, you add logarithms; and when you divide, you subtract logarithms, just as you do when you use logarithmic tables for these operations.

STEP 7 To square a number: Locate the number on the *D* scale. The square will be under the hair line on the *A* scale. Try these:

$$22^2 \qquad (0.395)^2 \qquad 8.18^2$$

STEP 8 To find square root: Locate the number on the *A* scale. The square root will be on the *D* scale. Suppose you wish to find the square root of 572. At this point you are in trouble because you can locate 572 in two places on the *A* scale, and each case gives you a different result on the *D* scale: 239 and 756 (decimal point not yet located). Which is correct?

To answer this, group the digits in 572 as you would if you were to use arithmetic to find the square root:

$$\sqrt{5\quad 72\overset{\cdot}{.}}$$

The square root of 5 is between 2 and 3. Immediately you know that the square root of 572 starts with 2, and that it has two digits before the decimal point. The answer is 23.9.

Find the following:

$$\sqrt{45} \qquad 3\sqrt{28}$$

$$\sqrt{450} \qquad \frac{15}{\sqrt{46}}$$

STEP 9 Trigonometric functions: Since slide rules made by different companies handle the trigonometric functions differently, the best way to learn how to compute with these functions is to read the instruction book that comes with the slide rule.

Do not try to learn all about the slide rule at first. Master the fundamental procedures, then try the more advanced ones described below.

STEP 10 Everything in the *CI* scale is the reciprocal of the number below it on the *C* scale. Find 5 on the *CI* scale. Its reciprocal is 1/5 or 0.2, which you will find on the *C* scale. Similarly, if you find 5 on the *C* scale, you will see the reciprocal, 0.2, on the *CI* scale. When you use the *CI* scale, be sure to notice that the low numbers are at the right, the high ones at the left. You can use the *CI* scale for multiplication and division. For example:

$$27 \times 4.23 \times 514$$

Solve this problem using *C* and *D* scales. Every time you move the hair line or the *C* scale, count one move. It will take 5 moves.

Now do it this way:

$$\left(27 \div \frac{1}{4.23}\right) \times 514$$

If you do the problem correctly, using the *CI* scale, you will get the same answer as before, but it will take 3 moves instead of 5:

a) With the hair line, locate 27 on the *D* scale.

b) Move the sliding scale until 4.23 of the *CI* scale is under the hair line. The reciprocal of 4.23 ($1/4.23 = 0.236$) will be below the hair line on the *C* scale.

c) Move the hair line to 514 on the *C* scale and read the answer (5.87×10^4) on the *D* scale.

Make up additional problems to practice the use of the *CI* scale.

STEP 11 Invent a way to use the *CI* scale with division. Try problems like this:

$$\frac{17}{0.056 \times 4.27 \times 1.039}$$

STEP 12 Invent a way to use the *C* and *D* scales alone to find square root.

STEP 13 When you have a problem involving a variety of procedures, it is a good idea to decide first what order of operations will be most economical. For example:

$$\frac{32\sqrt{7.4 \times 3.18}}{1.4 \times (2.7)^2}$$

One way to compute is this:

a) Find $7.4 \times 3.18 = 23.5$
b) Find $\sqrt{23.5} = 4.85$
c) Find $(2.7)^2 = 7.29$
d) Rewrite the problem as $\frac{32 \times 4.85}{1.4 \times 7.29}$ and solve.

A faster way is this: Use *A* and *B* scales to multiply 7.4×3.18. You know that $7 \times 3 = 21$, and that the square root will therefore be 4+. Consequently, you use the end of the *A* and *B* scales that will give you an answer that is directly above the 4 to 5 section of the *D* scale. You now have $\sqrt{7.4 \times 3.18}$ on the *D* scale and can proceed with the rest of the problem. It is not necessary to determine $(2.7)^2$. Just divide by 2.7 twice.

Try this problem in several ways. You should get the same answer each time: 15.21. (Of course, only 2 digits are significant in this answer, but test your slide-rule skill by trying to obtain all four.)

INVESTIGATION

4

Accelerated Motion

Introduction

You probably know that if you drop a ball from an upstairs window, it picks up speed as it falls. If you let a cart roll downhill, it goes faster and faster. These are examples of **accelerated motion,** motion with a change in velocity. In this investigation you will study the accelerated motion of an object that is falling through the air or rolling down a slope.

Equipment

Any device that shows successive positions of a falling or rolling body at equal time intervals. Since different schools will have different equipment, your teacher will show you what you are to use and how to use it.

Procedure

In order to study accelerated motion, you must have some way of measuring the speed of an object at various times. A freely falling object goes so fast that it is difficult to make careful observations. Galileo, who was the first to make a scientific investigation of accelerated motion, used a ball rolling down a slope because it accelerates less rapidly than when it falls. Even in this case, the measurement of speed is complicated.

If you are in a car that is speeding up, you notice that the speedometer reading keeps changing. For example, it might go from 10 miles per hour, to 20, to 30, and so on. At any moment, you can read the speed from the speedometer. Unfortunately you cannot attach a speedometer to a falling ball or to one rolling down a slope, so you have to figure the speed indirectly.

Before you start your investigation, read through and answer the questions at the end of this paragraph. They will help you to understand how the speed of an accelerated body can be estimated. Suppose a ball is rolling down an incline. You note where it is at one instant, and where it is exactly 2 sec later. By measurement you find that it has rolled 60 cm during the 2 sec. Call the time when you first noted its position Time 0, and the time 2 sec later Time 2.

a) What was the average speed of the ball during the 2 sec?
b) Was it going at that speed, or slower, or faster at Time 0?
c) Was it going at that speed, or slower, or faster at Time 2?
d) When might it actually have been traveling at that speed?

Before you continue with the investigation, have your answers to these questions checked by your teacher. Be sure that you understand them.

STEP 1 Examine the equipment you are to use. In what direction is the object accelerated? How are you going to measure distances in the direction of acceleration? How are equal time intervals determined? The answer to this last question depends on the apparatus. Does your apparatus do it in any of these ways? **a)** A spark jumps from a falling object to an upright post, burning holes through the paper at equal time intervals. **b)** An electric bell clapper makes marks at equal time intervals on a moving strip of paper that is pulled by a falling weight. **c)** A steel ball is propelled horizontally onto a sloping surface and leaves a record on

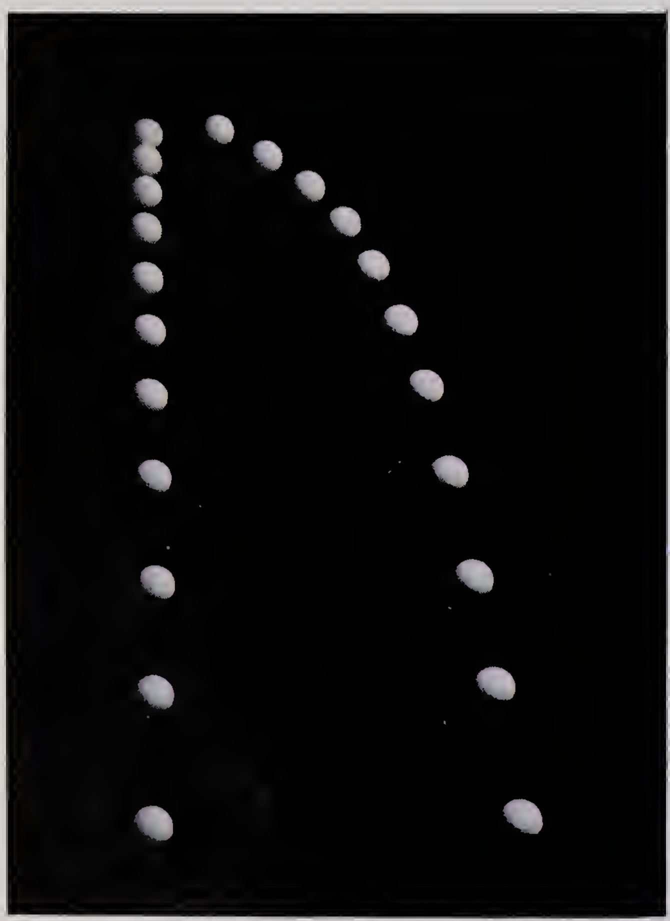


Fig. 4–1 The two balls in this photograph started to drop at the same instant. The ball at the right was also given a horizontal push. A flashing light exposed the film at equal time intervals. Note that the ball at the right moved equal distances horizontally in equal time intervals.

Time	Position (cm)			
0	10.00			
1	12.38			
2	15.89			

paper taped to the surface when carbon paper has been placed over the paper. In this case, the ball moves equal distances horizontally in equal time intervals. Figure 4–1 is a photograph that shows this to be true. **d)** A ball bounces back and forth across a groove in a board as it rolls down the slope. Each back-and-forth motion takes the same amount of time.

Observe the operation of the equipment until you understand how it makes the record.

STEP 2 Use the equipment to make a record. Decide what time interval you wish to use (for example, 2 spark intervals; 4 bell claps; 2 horizontal inches; one complete back-and-forth motion of the ball in a groove). Select an interval that gives you at least 8 positions of the accelerating object. Select a starting position (which may be either when the object was at rest or after it started to move), and call it Time 0. Number the other positions 1, 2, 3, etc. Using the rules for measurement, which you learned in Investigation 2, measure the position of the ball at each of these times and record your measurements in your *Data Book* in a chart like the one shown here. Extra columns should be included for later use in case you need them.

Notice that the first position is given as 10.00 cm. For an explanation, see Rule 4 in Investigation 2. Notice also that the position is always measured from the starting position, not from position to position. Thus, in the data chart shown here, the object moved 2.38 cm between Time 0 and Time 1, and 3.15 cm between Time 1 and Time 2 (15.89 cm − 12.38 cm). The *Position* column is marked cm to show that all of the positions are measured in that unit. The *Time* column is not labeled with a unit because the size of the unit is not important in this investigation, and it may even be unknown (if you do not know the frequency of the spark or how fast the bell vibrates, for example). However, you should record in your *Data Book* what you do know about the time unit, with a statement like this: Time unit is 1/10 sec (or 4 claps of the bell, or 2 sparks, or time for the ball to roll 2 inches horizontally, etc.).

STEP 3 Find the average speed of the object during each time interval, in cm per time unit. In order to tell more clearly just how the speed is changing, graph the speed against the time. When you do this, be sure to put the average speed on the graph at the time when it is most likely that the moving object actually had this speed. If necessary, reread *Before you start your investigation.* See Appendix 3, *Rules for Graphing Experimental Data.*

Discussion

1. Do you have evidence that the object was accelerated? What is the evidence? If the speed increases at an even rate, the object is said to be **uniformly accelerated.** Was your object uniformly accelerated or not? Give reasons for your answer.
2. Does your graph give evidence that there was experimental error in the experiment? Explain. If the answer is "yes," suggest possible causes of experimental error.

3. Could your graph be used to find the speed at Time 0? How? Could it be used to find how long before Time 0 the object started to move? How?
4. The acceleration of a moving object is given by the equation:

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time during which the velocity changed}}$$

Use your graph to find the acceleration. In what units should your result be expressed? Why is it better to determine the acceleration from the graph than from your data sheet? How can you use the graph to make the calculation as accurate as possible?

5. Why was it better to measure the distances to each position from the starting point instead of from each position to the next?
6. What unproved assumptions did you make, if any, during the course of this investigation?

INVESTIGATION

5

The Period of a Pendulum

Introduction

In its simplest form, a pendulum is a weight (pendulum bob) hung on a long string. Nearly 400 years ago, Galileo discovered that a pendulum keeps good time. He used a pendulum to measure time in some of his experiments. Since a pendulum swings in a shorter and shorter arc and comes to rest unless it gets a new push from time to time, the building of a pendulum clock was a difficult problem. When he was an old man, Galileo did design a pendulum clock, but he never built it, so the honor of inventing a working clock of this sort goes to another man, Christian Huygens, who lived in the 17th century.

The length of time for a pendulum to make one complete swing (for example, from one end of the swing to the other and back to the beginning) is called its **period.** Your problem is to investigate some of the factors that might influence the period of a pendulum, particularly its length, its mass, and the angle through which it swings. There may be other factors, of course. Be prepared to suggest some later.

Equipment

Balls of brass, iron, aluminum, or other materials that can be suspended; string; support; stop watch or electric timer.

Procedure

Before you start the investigation, make a guess about the way in which each of these three factors influences the period. There is no penalty for a wrong guess. A scientist often sets up a hypothesis, only to find that it is a false one, and he learns as much in this way as when the hypothesis turns out to be true. In your *Data Book*, write three hypotheses, to express your guesses about the effect of each of the three factors on the period of a pendulum.

The three factors you are investigating must be varied one at a time. If two were varied at the same time, you would not know whether the change in the behavior of the pendulum was due to one or both factors.

The class should be divided into three groups, each investigating a different factor.

STEP 1 How is the period of a pendulum affected by its length? Using a metal ball and a piece of string, make a pendulum that is 10 cm long, measured from the pivot point to the center of the weight. Displace it 2 cm (1/5 of its length) from its resting position and measure the time required for the first 20 complete cycles (swings across and back). Repeat with pendulum lengths of 20, 25, 50, and 100 cm. Be sure to keep all the other factors constant: use the same metal ball, displace it 1/5 of its length, and time the first 20 cycles. Record your data in a table with columns for length (l), time for 20 swings, and period (T).

STEP 2 How is the period of a pendulum affected by its mass? For these observations you must keep all factors constant except the mass of the pendulum bob. Use a pendulum. of constant length (measure it each time, since heavy weights may stretch the string). Always displace the pendulum the same amount and, starting immediately after the pendulum is released, always count 20 complete cycles (across and back). In your *Data Book* make a suitable table and record the data.

STEP 3 How is the period of a pendulum affected by the angle through which it swings? Here everything must be kept constant except the angle. Start with the pendulum only very slightly displaced, then displaced about 15°, about 45°, and about 90°, and count 20 complete cycles (across and back). In your *Data Book* make a suitable table and record the data.

Discussion

1. Is the period of the pendulum affected by the factor you investigated? As the factor (length, mass, or length of path) increased, did the period increase, decrease or stay the same?
2. If the factor you investigated did influence the period, try to find more about the relationship. When you graph the two quantities, is the relationship a straight line? If it is, the relationship is said to be *linear*, and changes in the two quantities are proportional to each other. If the graph has definite curvature, then the relationship is *nonlinear*.
3. Summarize in your *Data Book* the results of investigations of the other factors made by other students. What is the influence of those factors on the period of a pendulum? Is the relationship linear or nonlinear. If your factor had no influence, graph the data for a factor that did.
4. What other factors, not investigated by you or your classmates, might influence the period of a pendulum?
5. What was the advantage in timing 20 swings of the pendulum instead of only one? Why, in Step 1, was the pendulum deflected 1/5 of its length each time, instead of the same number of cm each time?

For Further Investigation

1. Select a set of data, your own or from one of the other groups, that shows a nonlinear relationship when graphed and attempt to determine the nature of the relationship. To do this, you try to change one of the variables in such a way that you can make a straight-line graph. For example, suppose you have graphed two variables, x and y, and find you have a curve. You set up the hypothesis that changes in y are proportional to changes in x^2. Therefore you make a new data column, headed x^2 and calculate all the values. Then you graph y and x^2 together. If the result is a linear graph, then you know that changes in y are proportional to changes in x^2. Furthermore, if the graph goes through 0, 0, you know that y is proportional to x^2, or $y = kx^2$, where k is a constant of proportionality.

   If that change does not produce a linear graph, you can change x to $\frac{1}{x}$, or $\sqrt{x}$, or $\log x$, or a trigonometric function if x is an angle. There are many possibilities. The object of such an investigation is to write an equation that properly expresses the relationship between the variables.
2. Use your data to find the value of the acceleration of gravity (g) in your location. Do not attempt this until you have learned the meaning of g. Then look up the equation for the period of a pendulum and see how you can use it to evaluate g. Observe rules for significant digits in reporting your result. How could you improve the accuracy of your observations so that you would be justified in reporting more significant digits?

INVESTIGATION

6

Precision Measurement of Length

Introduction

With an ordinary meter stick you can measure distances to the nearest mm, making a guess about the nearest 0.1 mm. Sometimes, however, you may wish to measure objects, particularly small ones, with much greater precision. Furthermore, some distances, such as the diameter of a wire or the size of a small hole, are inconvenient to measure with a ruler. Many kinds of linear measurements can be made precisely and conveniently with the *vernier caliper* and the *micrometer caliper*. The purpose of this investigation is to teach you how to use these instruments; and when you feel reasonably sure of your ability, your teacher will check your accuracy by having you measure some objects he has already measured.

Equipment

Vernier caliper (metric), micrometer caliper (metric); miscellaneous objects to be measured (such as coins; window glass; marbles; wire; glass tubing; sheets of paper; human hair; pencils.

Procedure

A. HOW TO USE A VERNIER CALIPER

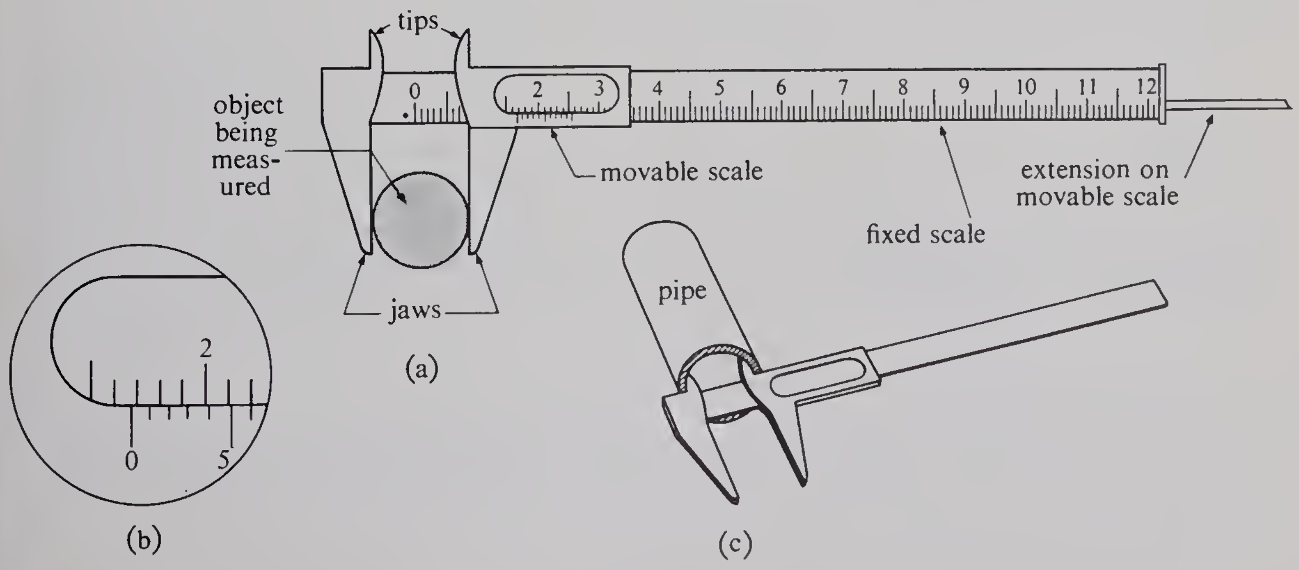
STEP 1 Examine your vernier caliper. For names of the parts see Figure 6–1a. Notice that there are two scales, a fixed one and a movable one. The fixed scale may have both metric and English units. In this investigation you will use the metric units. Examine the metric scale. **a)** Is the distance between the mark numbered 0 and the mark numbered 1, 1 mm, 1 cm, or 1 m? **b)** On the metric scale is the size of the smallest division 0.1 mm, 1 mm, or 1 cm? If you are not sure about the answers to these questions, check with your teacher.

STEP 2 The movable scale is called a **vernier**. There are 10 divisions on the edge of the vernier touching the fixed metric scale. The line at the far left is the 0-line. With no object between the jaws, run the vernier scale to the left as far as it will go. Then the 0-line of the vernier should be exactly opposite the 0-line of the fixed scale. If it is not, there is something wrong with your caliper and you should report this to your teacher.

STEP 3 **a)** Now set the 0-line of the vernier exactly opposite the 1 of the fixed scale. What is the distance between the jaws? **b)** Next set the 0 of the vernier exactly opposite the first short line after the 1 of the fixed scale. What is the distance between the jaws?

STEP 4 In Fig. 6–1a, with an object between the jaws, the 0-line of the vernier is not exactly opposite any of the lines on the fixed scale. It is between 1.6 and 1.7 cm. Therefore the diameter of the object is between these values. The vernier scale makes it possible to determine accurately, not by guesswork, the third digit in the measurement. To do this, find that pair of lines, one on the fixed scale and one on the vernier, which most nearly coincide. In Fig. 6–1b line 6 of the vernier nearly coincides with a line of the fixed scale. Therefore the caliper reading is 1.66 cm, accurate to the nearest 0.01 cm.

Fig. 6–1 The vernier caliper. In **a.** the caliper is used to measure the diameter of a cylinder; **b.** is a magnified view of a part of the movable scale next to the fixed scale, showing that the diameter of the object is 1.66; **c.** shows how to make inside measurements.



STEP 5 If you wish to measure the inside diameter of a hole, put the tips of the caliper in the opening, as shown in Fig. 6–1c. Read the answer in the same way as before.

STEP 6 Use the vernier caliper to measure several objects. In measurements made with a vernier caliper the possibility of a mistake can be reduced if several readings are taken. Furthermore, the object being measured (a piece of windowglass, for example) may not be of uniform thickness. For these reasons, go through the complete process of each measurement at least three times, making the measurement at different places on the object. Record your observations in a neat table in your *Data Book*, and average each group of measurements. In the section at the beginning of this book, read *To the Student 3*(*d*) for a suggested form for the table.

STEP 7 When you think you know how to use the vernier caliper, try your skill with several objects previously measured by your teacher, so that your accuracy can be checked. Record your results in your *Data Book*. Be sure to identify each object by name and number so that your teacher can check your measurements.

B. HOW TO USE A MICROMETER CALIPER

STEP 1 Compare your caliper with Fig. 6–2. Turn the handle until you can see the numbers 5 and 10 on the scale of the sleeve. Does the 10 on the sleeve mean 10 in., 10 cm, or 10 mm?

STEP 2 Examine the numbers on the thimble scale. How many divisions are there in the complete circle around the thimble scale?

STEP 3 **a)** Set the 0 of the thimble scale opposite the 8 of the sleeve scale. The number 8 may not be marked on the sleeve. You have to determine it from the location of the 5 and 10. Now turn the knob until the 0 is opposite the 9 of the sleeve scale. How many complete rotations of the thimble scale were required? **b)** In moving from 8 to 9, the edge of the thimble moved 1 mm to the right. Through how many scale divisions of the thimble did you turn the thimble? **c)** Is the value of a single scale division on the thimble 1 cm, 1 mm, 0.1 mm, 0.01 mm, or 0.001 mm?

STEP 4 Set your caliper so that it reads each of the following values: 8.25 mm, 8.75 mm, 8.17 mm, 8.67 mm, 8.04 mm, 8.54 mm. If you are doubtful about how to make these settings, consult your teacher. Friends may also be able to help you.

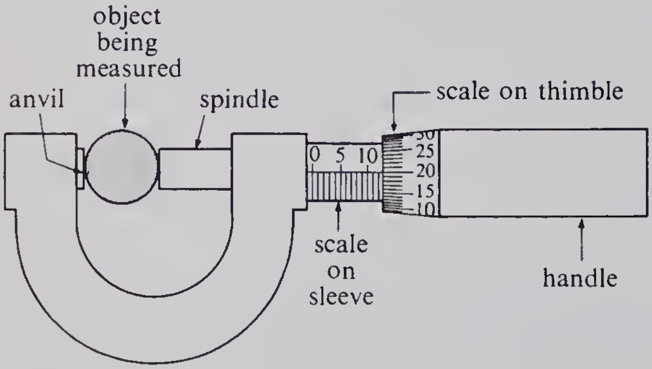


Fig. 6–2 The micrometer caliper.

STEP 5 If you bring the anvil and spindle together too tightly, you can damage the instrument. To avoid this possibility, grasp the handle so lightly with thumb and fingers that your fingers slip as the jaws come together. With practice your fingers will slip when the micrometer is adjusted to the same degree of tightness on each measurement. This skill will permit you to make consistent readings. Some instruments have a ratchet on the handle, which slips as the jaws come together. Be sure to use the ratchet handle if there is one, and always let it click the same number of times.

It is unlikely that the thimble scale will read 0 when the jaws are together. Examine Fig. 6–3 to see how to record your 0-error. Note particularly (d), which shows how to estimate to the nearest 0.001 mm. Make at least three readings of the 0-error, record them in the *Data Book*, and compute the average.

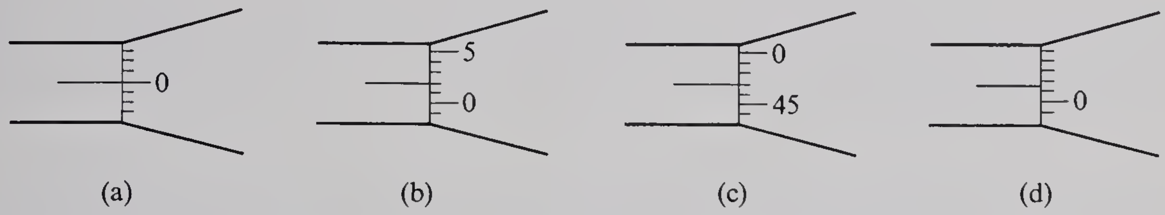


Fig. 6–3 How to determine the 0-error. **a.** The 0-error is 0 mm; **b.** the 0-error is 0.02 mm. **c.** the 0-error is −0.03 mm. **d.** If the 0-error is between two marks on the thimble, estimate its position. Here it is 0.014 mm.

STEP 6 Place an object between the anvil and spindle. In order not to damage the instrument or the object, use the same technique as you did to bring the jaws together. Record the reading in a table in your *Data Book* similar to the one described in *To The Student 3(d)*. Estimate to the nearest 0.001 mm. Do not correct the reading, but record exactly what you read, even if the 0-error is not 0. With micrometer calipers it is customary to take 10 readings, since the instrument is capable of registering very small differences in length, and the average of 10 readings is therefore much more accurate than the average of only 2 or 3. The 0-error is then *subtracted* from the average. Thus, if the average is 14.724 mm and the 0-error is 0.015 mm, the corrected value for the length is 14.724 mm − 0.015 mm, or 14.709 mm. If the average is 28.389 mm and the 0-error is −0.027 mm, the corrected value is 28.389 mm − (−0.027 mm), which is 28.389 mm + 0.027 mm, or 28.416 mm.

Practice using the micrometer caliper to measure various objects. You might trade objects with other students, and compare results. Record all of the data in your *Data Book*. When you think your skill is good enough, ask the teacher for an object he has already measured. Record your measurements in your *Data Book*, being sure that you identify the object by name and number. Your teacher will tell you how many of the test objects he wants you to measure.

Discussion

1. If you wanted to measure the diameter of a 5-cent piece as accurately as possible, would you prefer to use a vernier caliper or a micrometer caliper? Why?

2. To make each of the following measurements as accurately as possible, would you use a meter stick, a micrometer caliper, or a vernier caliper? **a)** diameter of a golf ball; **b)** length of a table; **c)** diameter of a human hair; **d)** thickness of a piece of paper; **e)** inside diameter of a hole as big around as your little finger; **f)** inside diameter of a barrel.
3. In this investigation you averaged the several measurements of each distance. In what two ways is the average of several readings likely to be better than a single one?
4. Why was it desirable to use 10 readings for the micrometer caliper but only 3 for the 0-error and for the vernier?
5. How could you use a vernier caliper to measure the thickness of a single sheet of paper?

For Further Investigation

1. Teach yourself to use a vernier caliper marked in inches. Measure and record in inches some of the distances you have already measured in cm or mm. To check your skill, convert the English units into metric units and compare your answers with your original measurements in metric units.
2. How many divisions on the fixed metric scale of the vernier caliper are spanned by 10 divisions of the movable scale? How many divisions are there on the movable scale for English units? How many divisions on the fixed scale do they span? If you wanted to measure something in twelfths of the smallest division on a fixed scale, how many divisions should there be on a vernier scale? How many fixed scale divisions should they span?
3. If you answered Question 2, can you figure out why the rule that governs the design of the vernier works?

INVESTIGATION

7

Weight and Mass

Introduction

Every object on earth has both mass and weight. It may surprise you to learn that the two words do not mean the same thing to a physicist. It is the purpose of this investigation to help you to understand the difference between the concepts of weight and mass.

You can learn something about these quantities by measuring them. If you wish to measure them very exactly, you need precise instruments. You can compare several weights or several masses, however, by using your hand as the instrument. As you follow the procedure for this investigation, see what conclusions you can draw about mass and weight. These questions may guide your thinking: Does this quantity (mass or weight) have a direction? (A push or a pull, for example, has a direction, whereas a volume has not.) If one object has a greater weight than another, does it also have a greater mass?

This investigation may look so simple to you that you think it foolish, but the ideas involved are of great importance and are also ones that students often find hard to understand. Most of the investigation centers in the *Discussion*. If you will think through these questions carefully, you will not be confused later by the difference between weight and mass.

Equipment

Tin-can buckets; rods from which buckets can be suspended; laboratory weights; string; gummed tape.

Procedure

In this investigation you are not trying to define either weight or mass. Instead, you will be given some partial definitions of these quantities, and your job is to try to understand what these definitions mean. The definitions are **operational definitions;** that is, they describe an operation or test that you can use in order to measure the quantity.

> *To test for weight: Lift the object and see how hard it pulls on your hand.*
> *To test for mass: Push the object to give it speed, or try to slow it down, and see how hard you have to push.*

STEP 1 Put weights in 4 tin-can buckets until each contains one of the following amounts: 500 g; 1000 g; 1500 g; 2000 g. Tape a label to the bottom of each can to identify the weight. Put crumpled paper in the top of each can so that you cannot see the weights.

Have someone rearrange the cans while you are not looking. Then lift each can in turn and arrange them from lightest to heaviest. Compare your arrangement with the labels on the bottom. How does the order in which you have arranged them by weight agree with the order of the amounts on the label? Record your observation in your *Data Book.*

STEP 2 Mix up your cans and label them *A*, *B*, *C*, and *D*. Suspend each of them by a string at least 40 cm long and far enough apart so that when they swing, they are not likely to bump into each other. Now give each can a horizontal push. It is harder to start some cans than others?

Stop each can in the same way and with the same hand. Are they equally easy to stop?

Continue testing the cans, each time being sure that the can is stationary when you start to push it or that all are going at the same speed when you stop them. Arrange the cans from the one with the least mass to the one with the greatest mass. How does the order in which you have arranged them by mass compare with the order in which you arranged them by weight? Record your observations in your *Data Book.*

Discussion

1. A quantity that has magnitude only is called a **scalar** quantity. A quantity with both magnitude and direction is called a **vector** quantity. Is weight a vector or a scalar quantity? If it is a vector quantity, in what direction does it act? What observation made during this investigation supports your answer?
2. Every object resists being started and resists being stopped. This resistance to a change in velocity is called the **inertia** of the object. When you tested for mass, you were testing

inertia. Mass is often called the quantitative measure of the inertia of an object. Does the inertia of an object seem to act in a particular direction? Before answering this, ask yourself whether a can has inertia, no matter what the direction of the push you give it. Is mass a scalar or a vector quantity?

3. If one object has greater weight than another (when both are in the same place), does it also have greater mass? Give reasons based on your observations.
4. Why was it important in this investigation that all of the cans be the same size?
5. The weight of an object is the result of gravitational attraction between the object and other objects. Since your investigation is carried on at the surface of the earth, the largest gravitational force acting on it is that between the object and the earth, but it is also attracted by the sun, moon, and even by other objects in the room. Compare the direction of a weight in the United States with the direction of a weight in Austrialia.
6. If you were a hundred miles above the earth, would you expect your weight to be exactly the same as it is when you are on the ground? Why? What would you expect on the moon?
7. In the part of the procedure used to test mass, it was important that the weight of a can should not interfere with your ability to feel its inertia. How was this done?
8. If you could put yourself in the right location between the earth and the moon, your weight would be zero. Explain.
9. You feel your weight because of the pressure exerted on your body by whatever is supporting you. If you jump from a height, there is no pressure on you until you hit the ground. Therefore, while you are falling, you feel weightless. An astronaut coasting in space when the rockets on his ship are turned off feels no pressure to give him a feeling of weight. He feels weightless, but does he have zero weight? Give reasons for your answer.
10. Remember that the investigation was set up in such a way that weight was not involved when you were testing for mass. Suppose that you were able to take your 2000-g can to a place where its weight was zero. If the can still contained all of its original material, would its mass be changed? Would it be easier or harder to set it in motion than on earth? Give reasons for your answer.
11. The objects marked 100 g, 200 g, etc., that you put in your cans are called laboratory weights. Some people think they should be called laboratory masses. Which term do you think is more accurate? Why?
12. Examine the various instruments used for weighing in your laboratory. You will probably find both beam balances and spring balances. Which balances truly measure weight, and which use the weights of objects in order to make a comparison of masses? Which type of balance would give the same reading on the moon as on the earth? Which would give different readings in the two places? Why is it possible to use weights to compare masses?
13. In a vault in France, there is a metal cylinder called the International Standard Kilogram. Almost all of the countries of the world base their measures of mass and weight on this cylinder. Is the cylinder more reliable as a standard of mass or of weight? Why? How could you use it as a standard for both?

INVESTIGATION

8

Force and Acceleration
Metric Units of Mass and Force

Introduction

As you learned in Investigation 1, the velocity of any object remains unchanged unless an unbalanced outside force acts upon it. The question you will investigate in this experiment is: What happens when an unbalanced force does act on an object? You will also be introduced to the metric units of mass and force.

The simplest answer to the question of how an unbalanced force acts on an object is that the velocity changes. In other words, there is acceleration. The size of the force should have something to do with the acceleration, and so should the mass of the object. In this experiment you will therefore investigate the relationship between the force and the acceleration.

Before starting the experiment, make a guess about the way in which the force influences the acceleration. Choose your hypothesis (no penalty for a wrong guess). When an unbalanced force acts on an object, it produces an acceleration that is **a)** directly proportional to the force; **b)** inversely proportional to the force; **c)** related to the force in some more complicated way. Write the selected hypothesis in your *Data Book.*

Equipment

Weight hangers, slotted weights (totaling 2.4 kg for each group of students, at least 100 g of which are 10-g and 20-g weights); nonstretching and nontwisting cord (nylon fishline recommended); single fixed pulley with low friction and light weight; stop watch; meter stick. The pulley must be wide enough so that weight hangers, hung as in Fig. 8–1, do not bump each other when they pass.

Procedure

Before you start your investigation, answer the following questions in your *Data Book* and have the answers checked. You will not be graded on your answers. It is important for you to have the correct answers and to understand why they are correct because then you will understand better how to carry out the investigation.

a) In this investigation you should record masses in kilograms; although they will probably be marked in grams. Convert the following quantities from g to kg (see Appendix 5): 1200 g; 780 g; 250 g; 40 g; 10 g; 3 g.

b) Weight and mass are not the same thing. Weight is a force, caused by the gravitational attraction between masses, while mass is a measure of the inertia possessed by an object. Just as there is in the metric system a special unit of mass, the kilogram, so there is also a special unit of force, the newton (N), which will be defined later. However, in the laboratory you will often measure weights in kilograms or grams instead of in newtons. A force of 1 kg is equal to the weight of a 1-kg mass at the surface of the earth (more precisely, at a spot where the acceleration of gravity is

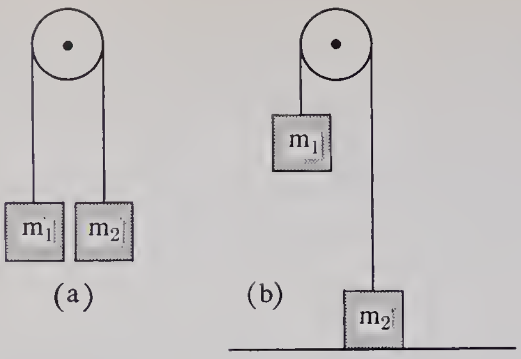


Fig. 8–1 Notice in **b** that m_1 will always descend the same distance if m_2 rests on the floor at the beginning of each trial.

9.80665 m/sec^2). Therefore you can use kilogram-masses and gram-masses in your laboratory to weigh things in kilograms of force (kgf) or grams of force (gf). The *f* is put in as part of the abbreviation to remind you that a force unit is being used. At the surface of the moon, does a 1-kg mass weigh 1 kgf, more than 1 kgf, or less than 1 kgf? Why?

c) In a space ship 1000 miles out from the surface of the earth, would a 1-kg mass weigh 1 kgf, more than 1 kgf, or less than 1 kgf? Why?

d) If m_1 and m_2 in Fig. 8–1 have the same mass, what will happen?

e) If m_1 is 1.500 kg and m_2 is 1.400 kg, what force in kgf is acting because of the difference in weights on the two sides of the pulley? What would you expect to happen as a result of the difference in weight?

f) Suppose that m_1 is 1.460 kg and m_2 is 1.440 kg. In spite of the weight difference, nothing happens. How can this be explained?

g) In the light of your answer to Question (**f**), what can you say about the size of the unbalanced force causing the change in velocity in Question (**e**)?

h) When there is motion caused by the difference in weight, what is the total mass that moves? (Ignore the mass of the pulley.)

i) If you start with the situation shown in Fig. 8–1b, and if m_1 is much larger than m_2, how far will m_1 move before stopping? How could you measure this distance?

j) Suppose you use a stopwatch to measure the time for m_1 to descend to the floor and get the following results: 3.2 sec, 3.1 sec, 3.9 sec, 3.1 sec, 3.0 sec, 3.2 sec. What would you do about the 3.9 sec measurement when you calculated the average time? Why?

k) If m_1 falls 1.00 m from its rest position in 5.0 sec, what is the acceleration? Show your method clearly in your *Data Book*, but do the arithmetic on another paper.

l) Since you are investigating the effect of force on acceleration, how can you arrange things so that the mass remains the same even though the force changes?

STEP 1 Set up apparatus as shown in Fig. 8–1. The pulley should be 1.20 m or more above the floor. Notice that the string must be just long enough so that when m_2 is resting on the floor, m_1 is almost up to the pulley.

STEP 2 Note that the mass of each weight hanger is printed on it. Add 1.200 kg to each weight hanger. Weight hanger m_2 should have at least 100 g in 10-g and 20-g units. (See your answer to Question (**l**).

STEP 3 Set up a chart in your *Data Book* like the one shown. Record the values of m_1

DATA CHART

m_1 at the beginning __________kg m_2 at the beginning __________kg

s (distance that m_1 travels when it descends) __________m

m_1 (kg)	m_2 (kg)	t (sec)	t (av) (sec)	a (m/sec^2)	f due to difference in weights (kgf)	Unbalanced f (kgf)
______	______	___ ___ ___ ___ ___ ___ ___ ___	______	______	______	______
______	______	___ ___ ___ ___ ___ ___ ___ ___	______	______	______	______

and m_2 at the beginning, and s. Note your answer to Question **(i)** if you are not sure how to measure s.

STEP 4 Move weights from m_2 to m_1 until the difference is sufficient to make m_1 travel from top to bottom in about 6 or 7 sec. Record the values of m_1 and m_2 on the first line of your data chart. With a stop watch measure the time (t) as precisely as possible. This is a measurement that is difficult to make with precision, since you must try to start the watch at the moment when the weight begins to descend, and to stop it at the moment when the weight hits the floor. The average of 5 such measurements is more likely to be accurate than a single measurement. There is room on your data chart for recording more than 5 measurements, so that if any measurement is obviously incorrect, it may be crossed out. See your answer to Question **(j)**.

STEP 5 Take 10 g more from m_2 and add it to m_1. Measure the time 5 or more times and record them on data chart. Repeat this step and continue to repeat it until m_1 is descending so rapidly that you can no longer make accurate measurements of the time.

STEP 6 Complete the rest of the columns on the data sheet, except for the one labeled "Unbalanced force." For calculating acceleration (a), see your answer to Question **(k)**. Calculate t (av) to one more digit than in the original measurements, since the average has more accuracy than a single measurement.

STEP 7 From your data sheet you cannot tell exactly the amount of the frictional force in the pulley wheel, but you can tell that it was less than a certain amount. Record the amount in the *Data Book*.

STEP 8 Graph the force due to the difference in the weights against the acceleration. (See Appendix 3.)

STEP 9 According to your graph, if the acceleration were 0, would the force due to the difference in weights be 0? Account for your observation.

STEP 10 What is the size of the force of friction in the pulley?

STEP 11 Complete the last column on your data chart and graph unbalanced force against the acceleration.

Discussion

1. If the mass of an object is held constant, what is the relationship between an unbalanced force and the acceleration it produces? What is your evidence for this conclusion? Compare the conclusion with your hypothesis. Was the hypothesis supported by your observations, or must it be discarded?
2. Why were you instructed to move weights from one weight hanger to the other? Why not just add weights to m_1 from another supply of weights?
3. Why was it possible to ignore the mass of the pulley?
4. When you used the distance traveled by m_1 and the time it took to descend, in order to calculate acceleration, what assumption were you making about the acceleration? Is this a reasonable assumption? Why?
5. Would this investigation work in a place where objects have zero weight? Why?
6. If you apply a force to a 1-kg mass that gives it an acceleration of exactly 1 m/sec^2, the force is 1 newton (N). Answer the following questions in order to determine the relationship between a force of 1 N and a force of 1 kgf.
   a) What force in newtons (N) will give an acceleration of 5 m/sec to a mass of 1 kg?
   b) What force in N will give an acceleration of 9.8 m/sec to a mass of 1 kg?
   c) If you are at the surface of the earth and you drop a mass of 1 kg from your hand, what is its acceleration?
   d) What force in N must be acting on a mass of 1 kg when you drop it at the surface of the earth?
   e) What force in kgf is acting on a mass of 1 kg when you drop it at the surface of the earth?
   f) 1 kgf = _?_ N.
7. There is another metric unit of force, the dyne. It is the force that will give a mass of 1 g an acceleration of 1 cm/sec^2. Using the same reasoning as in Discussion Question 6, tell how many dynes there are in 1 gf.

INVESTIGATION

9

Work and Power

Introduction

The words *work* and *power* have a variety of meanings in everyday use. To the physicist, however, each of these words means something very particular. It is the purpose of this investigation to give you an understanding of the physicist's definitions of these two concepts and to give you some experience in measuring them.

Equipment

Balances; stop watch; measuring stick; various objects to be used as loads.

Procedure

You will measure your own power when you perform two different tasks. You will not get the same result for both tasks.

Before you start your investigation, solve the four following problems and have your answers checked.

- **a)** A person weighing 175 lb climbs a flight of stairs that is 10.0 ft high vertically and 20.0 ft long parallel to the slope. How much work does he do?
- **b)** The same person climbs the stairs in 5.0 sec. What is his power in ft. lb/sec? What is his horsepower?
- **c)** A person lifts a load of 36 kg to a height of 5.0 m. How many joules of work does he do?
- **d)** If the same person does the work in 6.0 sec, what is his power in watts?

STEP 1 Measure your horsepower when running upstairs. You need to know your weight in pounds fully clothed. Measure the time in seconds and the distance in feet. Be careful about significant digits.

STEP 2 Measure your power in watts when lifting weights from the floor to the table. Any objects may be used for the load. Let the total load be at least 20 kg, with enough different objects so that several trips must be made to get all of them onto the table. Decide what data to measure. Convert the watts obtained to horsepower. (1 hp = 746 W.)

Discussion

1. Examine the results obtained by other students along with your own. Can a person operate at a power rate of 1 hp or better? If so, can he operate at this power for a long period of time? Give your reason.
2. Is the power rate greater for running upstairs or for loading weights onto the table?
3. Why is the power rate different in the two situations?

INVESTIGATION

10

The Mechanical Power Developed by an Engine

Introduction

People commonly speak of tractors and automobiles, of electric fans and locomotives in terms of their power. The power is sometimes stated in horsepower, sometimes in watts. Most engines have drive shafts, which rotate and which convey the power from the engine to the place where it is to be used. In this investigation you will measure the power output of such an engine.

Equipment

Small electric motor with pulley wheel; heavy spring balances; leather brake belt; revolution counter; stop watch or electric timer; device for measuring pulley diameter; support rods and clamps.

Procedure

Before you start your investigation: The equation for calculating power is:

$$P = \frac{\text{work}}{\text{time}} = \frac{Fs}{t}$$

where F is force acting perpendicular to distance s, and t is time.

Examine the apparatus shown in Fig. 10–1. The motion of the pulley wheel on the drive shaft of the engine is opposed by the friction of the leather brake, which presses against it. You must measure F, s, and t when the engine is turning. The questions that follow will help you to see how to make these measurements. Do not proceed with the investigation until you are sure you have the correct answers to the questions.

a) When the engine is turning, will the two spring balances read the same amount?

b) The direction of rotation of the pulley is shown in the picture. Compare the reading of the balance on the right with that of the one on the left.

c) How can you tell the size of the force exerted on the pulley wheel by the belt?

d) The force exerted by the belt stays in the same place while the pulley wheel moves. During one revolution of the wheel, the distance along which the force acts is the circumference of the wheel. How are you going to measure the circumference of the wheel? This must be discussed with your teacher in terms of the equipment available in your laboratory.

e) The pulley will turn so rapidly that you cannot readily measure the time for a single revolution. If you use a stop watch and a revolution counter, you can find the number of complete revolutions in a certain amount of time, perhaps 10 sec. If the pulley makes 300 revolutions in 10 sec, how could you find the total distance along which the force acts during that time?

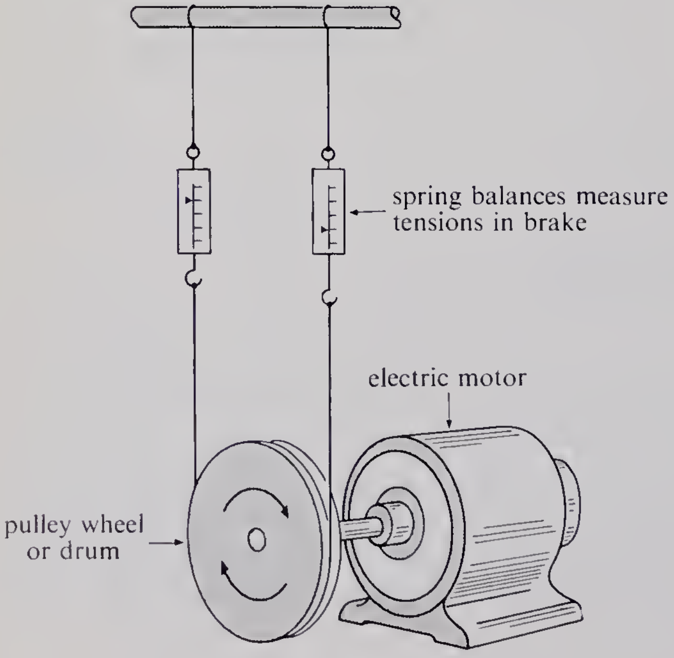


Fig. 10–1 A prony brake can be used to measure mechanical power simply and accurately.

STEP 1 Set up your apparatus as shown in Fig. 10–1 and practice using it. This experiment requires at least a two-man team, one to count revolutions and time, the other to maintain a constant tension as indicated by the spring balances. If these readings cannot be kept reasonably constant, it will be necessary to observe them at frequent intervals and compute the average values.

STEP 2 Prepare a data chart. Provide space to record pulley diameter in meters, time interval, number of revolutions, and readings on each spring balance.

STEP 3 Compute the power output of the motor in watts and in horsepower.

$$(1 \text{ hp} = 746 \text{ W.})$$

Discussion

1. Under what conditions would the two spring balance readings be the same?
2. F and s are supposed to be in the same direction. How can s be in the same direction as F if s is measured around the circumference of the pulley?

INVESTIGATION

11

Electric Charges

Introduction

When you shuffle across a rug on a day in winter, you can give a shock to a person whom you touch. When you comb your hair briskly, you may hear it crackle. If you take off a nylon shirt while you are standing in a darkened room, you may see flashes of light in the cloth. All of these phenomena are evidences of the electric nature of matter. Your body, the comb, your hair, and the nylon shirt each acquired an electric charge as a result of rubbing against another kind of material.

What kinds of electric charge exist? How do electric charges behave toward each other? How can you tell what kind of electric charge exists on an object? These are questions you will be able to answer after carrying out this investigation. You will find that there are many small questions asked as you proceed. They are set up in such a way that if you answer each one as you go along, you will find it easy to understand the investigation and the theory that scientists use to explain your observations. If you skip questions, you may get confused, so take each in turn.

Equipment

Strips of flexible vinyl plastic (the kind used for freezer and dry cleaner bags); strips of fiberglass curtain fabric or of acetate ribbon (the cheap kind used to tie gift packages); plastic bags large enough to fit over one hand; hard rubber rods; slings to support rods; string; fur; electroscopes.

A. KINDS OF ELECTRIC CHARGE

Procedure

STEP 1 Hold 2 vinyl plastic strips (or a single one folded over) and rub with the fingers, as shown in Fig. 11–1. What evidence do you see that the strips are charged? Both strips are of the same material and were charged in the same way. Therefore they must have charges that are alike. Do these two similar charges repel or attract each other? Call the charge on the vinyl strips charge *X*.

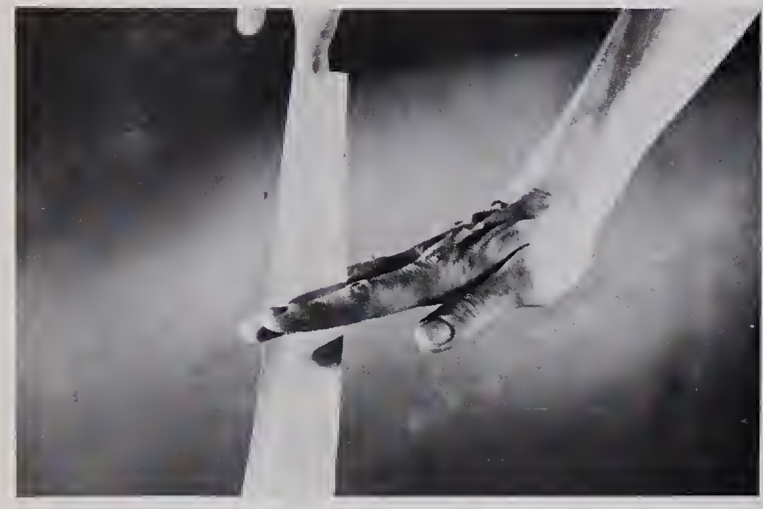


Fig. 11–1 Two strips of vinyl plastic can be charged by rubbing them briskly with three fingers.

STEP 2 Hold two fiberglass or acetate ribbon strips in one hand and stroke them with a plastic bag that completely covers the other hand. What evidence do you see that the strips are charged? Both strips are of the same material and were charged in the same way. Therefore they must also have charges that are alike. Do these two similar charges repel or attract each other? Since you do not know whether or not this is the same kind of charge as *X*, call it charge *Y*.

STEP 3 Charge the vinyl strips and suspend them by clipping or clamping them together at one end to a hanging string, with the loose ends free to deflect. Charge the fiberglass or acetate ribbon strips and bring them near the vinyl ones. Does charge *X* (on the vinyl strips) attract or repel charge *Y* (on the fiberglass or acetate ribbon)? Is charge *X* like or unlike charge *Y*?

STEP 4 Any names could be used for the two kinds of charge. Benjamin Franklin called them *negative* and *positive*, names still used today. Charge *X* (the kind that exists on the vinyl plastic) is called *negative*, and charge *Y* (the kind that exists on the fiberglass or acetate ribbon) is called *positive*. Suspend your fiberglass or acetate ribbon strips and keep them charged. Keep the suspended vinyl strips charged also.

You should be able to find out the kind of charge produced on various objects when you rub them. Try this for such objects as a hard rubber rod rubbed with wool, your comb just after you comb your hair vigorously, a wooden pencil, a plastic pen, a metal rod, or any other handy materials. Record in your *Data Book* the result of your investigation. Be sure to report in each case what was rubbed, what you rubbed it with, whether it attracted or repelled each of the hanging charged strips, and whether you think it has a positive or a negative charge. In some cases you may be uncertain about the charge. If so, report that fact. Make the data sheet as neat and clear as possible.

STEP 5 Charge a strip of vinyl plastic and bring it near some small bits of uncharged paper. What happens?

Charge a strip of fiberglass or acetate ribbon and bring it near some small bits of uncharged paper. What happens?

Discussion

1. How many different kinds of charge have you discovered in this experiment?
2. How do electric charges behave toward each other?
3. How do electric charges affect neutral (uncharged) material?
4. If some of the materials you tested in Step 4 attracted both kinds of hanging charged strips, what conclusion do you draw about the charge on those materials?
5. The theory that scientists use to account for the behavior of charged objects is this: All matter is made of atoms. Each atom has a positively charged nucleus surrounded by negatively charged electrons. The charge of the electrons is exactly equal to the charge of the nucleus, so the atom as a whole is neutral. The electrons are much lighter than the nucleus. When you rub two materials together, some of the electrons from around the atoms of one object are moved to the other object. Only the electrons move in this way, not the nucleus. Use this theory to explain **a)** how the vinyl strips obtained their charge, and **b)** how the fiberglass or acetate ribbon strips obtained their charge.
6. If you bring a negatively charged rod near neutral bits of paper, what effect would this charge be likely to have on electrons in the neutral paper? Although the paper as a whole would remain neutral, what kind of charge would tend to accumulate on the side of the paper away from the rod? What kind of charge would the paper tend to have on the side toward the rod? What kind of force (attraction or repulsion) would exist between the rod and the side of the paper nearest the rod?

B. THE ELECTROSCOPE

Procedure

STEP 1 An electroscope (Fig. 11–2) is a device for detecting electric charge, somewhat like your hanging strips. You can charge it by touching the knob at the top with a charged object. Charge the electroscope by touching it lightly with a charged plastic pen or rubber rod. This process is called **charging by conduction.** Warning: If you put too much charge on the electroscope, you may rip off the delicate metal leaves, so be careful. What happens to the leaves of the electroscope? Is your electroscope charged positively or negatively? How did the charge get from the knob down into the leaves? What kind of material is used to make the knob and the support for the leaves? Is this material a good conductor of charge (a conductor) or a poor conductor of charge (an insulator)?

STEP 2 To remove the charge from your electroscope, touch the knob at the top. Is your body a conductor or an insulator?

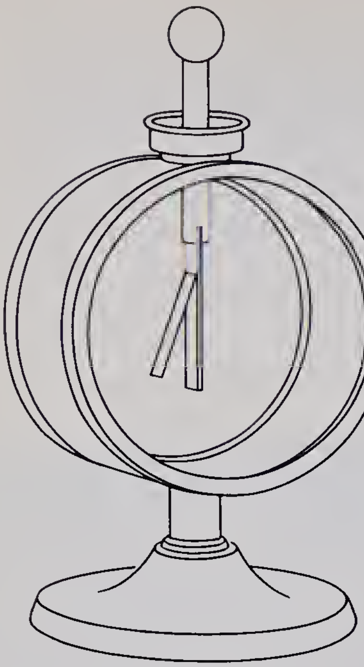


Fig. 11–2 An electroscope detects charge.

STEP 3 Charge the electroscope so that the leaves spread only part of the way. Bring a negatively charged object near the knob, without touching the knob. What happens?

Bring a positively charged object near the knob, without touching the knob. What happens?

Bring an object that has not been rubbed at all, and is therefore probably uncharged, near the knob of the electroscope, without touching the knob. What happens?

STEP 4 Rub one end only of a plastic pen or hard rubber rod. Test that end with the electroscope, and then the other end. What do you observe? Is the plastic or rubber a conductor or an insulator?

STEP 5 Suspend a metal rod in a sling attached to a string. Charge the rod at one end by touching it with a charged rubber rod or plastic pen. Roll the charged rod or pen around on the surface of the metal to get a sizable amount of charge on the metal. Bring the knob of the electroscope near each end of the metal rod. Is the metal rod charged at one end only or at both ends? Is the metal rod a conductor or an insulator?

STEP 6 This experiment must be performed exactly in the order given in the directions or it will not work. **a)** Charge a rubber rod or plastic pen and hold it in one hand. **b)** Put one finger of the other hand on the knob of an uncharged electroscope. **c)** Bring the charged rod near the knob, but do not let it touch the knob. **d)** Take away your finger from the knob. **e)** Take away the rod from near the knob. If at this point the leaves of the electroscope spread apart, showing that there is a charge, you have done the experiment correctly. Otherwise repeat the steps.

Is the charge on the electroscope positive or negative? Answer this question only after you have tested the electroscope in some way. Describe your test and the results. This method of charging is called **charging by induction.**

Discussion

1. According to your observations, what are some materials that are good insulators?
2. What are some materials that are good conductors?
3. When an electroscope is charged by conduction, does it have the same charge as the rod used to charge it, or an opposite charge?
4. When an electroscope is charged by induction, does it have the same charge as the rod used to charge it, or an opposite charge?
5. Use the electron theory to explain how the electroscope gets a negative charge by conduction.
6. Use the electron theory to explain how the electroscope gets a positive charge by conduction.

7. Use the electron theory to explain how the electroscope in Step B6 received a charge by induction.
8. If an electroscope has a positive charge with the leaves partly deflected, what should happen to the leaves when you bring a positively charged rod near the knob without touching it? Use the electron theory to explain your answer.
9. Why is an electroscope a better device for detecting the nature of a charge than the hanging strips you used in Part A of the experiment?
10. During the experiment with the uncharged bits of paper, you may have noticed that sometimes a piece of paper first clings to a charged object and then suddenly shoots off. How can you explain this phenomenon?
11. There are enough electrons in a silver spoon to electrocute more than two thousand people. Why are you not endangered by them?
12. Some companies experiment with "man-made lightning" to find ways to protect power lines and buildings from real lightning. To make the lightning, they put a very large negative charge on a hollow metal ball several feet in diameter, and another very large positive charge on a second ball. The balls are supported by insulators. When the charge is large enough, a gigantic spark jumps from one ball to the other. At such a time, a man can be inside one of the balls and not be in danger. Why is this possible?

For Further Investigation

1. How could you use a negatively charged rod to charge by induction two metal rods so that one of them has a positive charge and the other a negative charge? Try out your idea to see whether it works.
2. How can you prove experimentally that the inside of a charged metal container is a safer place to be than the outside?

INVESTIGATION

12

The Cloud Chamber

Introduction

If air is saturated with water vapor and then cooled, drops of water usually condense out of the vapor. Rain is formed in this way. However, it has been discovered that the drops form only if the air contains particles of dust or ions, either of which serve as nuclei around which the water condenses. If the air has no such particles, it can be cooled below the saturation point, and there will be no drops. In such a case, the air is said to be supersaturated.

Now suppose that a high-speed electron suddenly enters some supersaturated air. As the electron moves, it knocks other electrons from the atoms it passes and forms a string of ions along its path. Immediately, water condenses on the ions, and the path is marked by a line of tiny drops. If you are watching and if the drops are properly illuminated, you will see the path of the electron. This is the principle of the operation of the cloud chamber. Of course, the moving particle does not have to be an electron. It may be any moving charged particle that has enough energy to ionize the atoms in its path.

During this experiment you will observe the tracks made by various charged particles.

Equipment

Cloud chamber and associated equipment.

Procedure

STEP 1 Read the instructions for the use of your cloud chamber and follow them carefully.

STEP 2 Set up the cloud chamber to operate without any radioactive sample inside it. Watch the chamber for at least five minutes after it is ready to operate. Do you see any tracks? Make drawings to show what you see, and also describe the tracks in words.

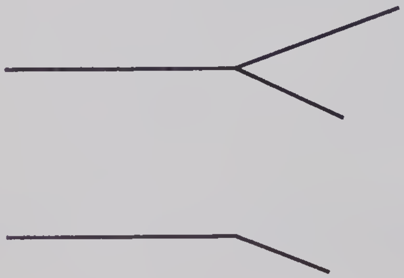
STEP 3 Insert various radioactive samples, one at a time. After you insert a sample, it may take several minutes before the chamber is again ready to operate, because of the dust particles that enter when you open the chamber. Compare the tracks formed by alpha particles (positively charged helium nuclei) with those formed by beta particles (electrons). Use words and drawings to record your observations.

Discussion

Particles capable of ionizing the air are given the name ionizing radiation.

1. Do you conclude from this investigation that there is always ionizing radiation (called background) in the air around you? What is the evidence for your conclusion?
2. If your answer to the first question was "Yes," suggest hypotheses about the origin of the background ionizing radiation.
3. Which tracks were quite straight? Which were very crooked? Suggest a hypothesis to account for the differences.
4. What kind of radiation creates the largest number of ions per centimeter of its path length? What is the evidence for your answer? Suggest a hypothesis to account for this observation.
5. Did you observe any tracks that suddenly changed direction or forked, as in Fig. 12–1? If you did, suggest a hypothesis to account for this?
6. Background radiation was discovered early in the 20th century, and its origin has been investigated ever since. Suggest some ways in which your hypotheses about its origin might be tested. You may suggest experiments that would be impossible for you to perform yourself but that someone else with better equipment might perform.
7. If you could put your cloud chamber between the poles of a powerful magnet (more powerful than any you are likely to have in your laboratory) the track of a charged particle would be bent into an arc of a circle.

Fig. 12–1 Sometimes the tracks in a cloud chamber look like these.



If you have the north pole of such a magnet above the cloud chamber and the south pole below it, negative particles (as seen from above) will travel in a clockwise arc, and positive ones will travel in a counterclockwise arc. How could such a magnet be used to tell which are alpha particles and which are beta particles?

8. "Cloud seeding" has been tried as a method to produce rain. What do you think the term means? How does cloud seeding resemble the operation of a cloud chamber?

INVESTIGATION

13

Background Radiation

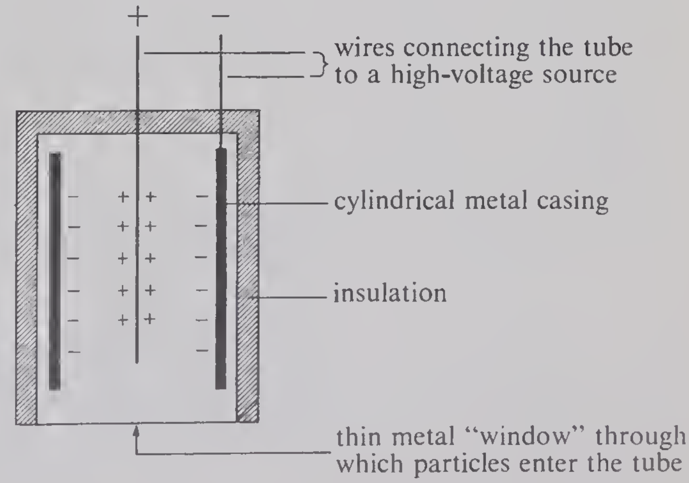
Introduction

Light and heat from the sun are forms of radiation; so are radio waves, cosmic rays, x-rays, and the rays from radioactive substances. These last three are called **ionizing radiation** because they have enough energy to ionize atoms. A small amount of ionizing radiation (largely due to cosmic rays) is always present at the surface of the earth. It is called **background radiation.** In this investigation you will measure the background radiation in your laboratory.

Figure 13–1 shows the design of a Geiger-Muller tube (sometimes called a Geiger tube). The wire down the center of the gas-filled tube is highly positive compared with the metal casing, but not quite positive enough to allow electrons to jump across from the casing. The "window" of the tube is a thin sheet of metal. If a high-speed electron hits the window, it will go through, ionizing the gas inside the tube. Negative ions are attracted to the wire, where they give up electrons and are neutralized. Positive ions are attracted to the casing, where they collect electrons and are neutralized. As a result, electrons flow into the rest of the circuit from the wire in the G-M tube, and flow away from the rest of the circuit into the casing. The flow lasts only a very short time. In the counter that you will be using, this sudden surge of electrons causes a click in the earphones or speaker. The tube is so designed that all of the ions formed by the entrance of one particle are neutralized in about 10^{-4} sec, after which the circuit is ready for the next particle. By counting the clicks, you can tell how many particles have entered the tube in a certain period of time.

Ionization of the gas can be caused by alpha particles, beta particles, or gamma photons. The window of your

Fig. 13–1 Geiger-Muller tube (cross-sectional view).


+
−
wires connecting the tube to a high-voltage source
cylindrical metal casing
insulation
thin metal "window" through which particles enter the tube

tube is probably too thick to allow alpha particles to enter, in which case your tube is used to measure beta and gamma radiation. While most of the beta and gamma radiations enter through the window, some may also penetrate the sides of the tube.

Background radiation is slight enough so that you can listen to the separate clicks and count them. If you bring a sample of a radioactive material near the counter, the clicks come too fast for you to tell them apart. For this reason your counter may have to register counts per minute (c/m). In this experiment you will count the clicks in each 10-sec interval for a 20-min period. Your purpose will be to measure the average background radiation in c/m and to decide how long you ought to count in order to determine a reliable average.

Equipment

G-M (Geiger-Muller) counter that produces audible clicks; watch or clock with a second hand.

Procedure

STEP 1 Read the operating instructions for the Geiger-Muller counter. These should be in a booklet supplied by the manufacturer or your teacher may prefer to explain them to you. Record in your *Data Book* the type of counter used and the kind of radiation measured by your counter.

STEP 2 Listen for the clicks, which tell you that particles are entering the tube. Practice counting the number of clicks in a 10-sec interval. Repeat several times to gain skill in counting.

STEP 3 Appoint one member of the group to be the clock-watcher. Set up a data sheet as shown. The clock-watcher says, "Now," as he begins to watch, and repeats the word, "Now," at the end of every 10 sec. Count the clicks you hear in each 10-sec period and

MEASUREMENT OF BACKGROUND RADIATION WITH GEIGER-MULLER COUNTER

Minute No.	Counts in each 10-sec interval						c/m				
1											
2											
etc. to 20											
	Total count in 20 min Average c/m (For the average c/m, record one digit after the decimal point.)										

record the number on your data sheet in pencil. It is not necessary to count steadily for 20 min. Rest periods can be taken, after which the counting is resumed. Have one person read his data out loud. If there is disagreement about how many clicks should be recorded for a particular interval, the verdict of the majority is probably correct.

STEP 4 You probably can observe that the values in the c/m column vary considerably. What is the highest value in that column; the lowest?

STEP 5 Suppose that your average is 16.3 c/m. Ten percent of 16.3 is approximately 1.6. Therefore any value between 14.7 (16.3 − 1.6) and 17.9 (16.3 + 1.6) would be within 10% of the final average. Perform a similar calculation for your average. How many of the values in the c/m column are within 10% of the final average?

STEP 6 From the calculations you did in Step 5, you can see that a 1-minute count is not very reliable. A reliable average should probably not differ from an average over a longer period of time by more than 2%. How long should you count to get a reliable average? There are several ways in which you might use your data to answer this question. Use the extra columns on your data sheet if you wish. Describe clearly the method you use to answer the question.

STEP 7 Cautiously bring a luminous-dial watch toward the G-M tube. (If you bring it too close, the needle of the tube may go off the end of the scale.) If possible with your equipment, determine the c/m for the watch dial. Compare the c/m from the face of the watch with that from the back, through the case. What is the effect of the case?

Discussion

1. To get a reliable average count, how long do you recommend counting? Give reasons for your answer.
2. When events like these clicks happen in an irregular way, with no particular pattern about them, they are called **random events.** To investigate random events, a scientist observes what he calls a **sample.** In this experiment your basic sample was a count for 10 sec. Six of these basic samples are combined to make a 1-min sample. Your whole experiment was a 20-min sample. What effect does the size of a sample have on the reliability of the information you can obtain from it?
3. Compare the c/m for the watch with the background c/m. Is the background dangerously high?
4. If you use the counter to test a sample that sends 100,000 particles per sec into the G-M tube, how would the tube behave?
5. Why can gamma rays, which are essentially like light rays with very short wavelength, be counted by a G-M counter?
6. Some radioactive samples are tested with the following results?

Sample A: 100 c/m
Sample B: 200 c/m
Background: 20 c/m

Compare the strengths of the two samples.

7. When the school bell rings at the end of the day, it is possible to predict with considerable certainty that in a very short time children will be pouring out of the building. However, it is not possible to predict with much certainty that Mary Jones will be one of the crowd. She might have been kept after school, or she may be staying for an activity, or she might have gone home early because she was sick. How are the certainty about the action of the children as a whole and the uncertainty about Mary's action in particular like the situation in the experiment you have just concluded?
8. Wearing a luminous-dial wrist watch is usually not considered to be dangerous, but many experts believe that there is danger in using a luminous-dial pocket watch. Why?

For Further Investigation

1. Make a frequency distribution for the counts you obtained for the 10-sec intervals. To do this, find how many times the count was 0, how many times it was 1, 2, 3, etc. Make a bar graph of the distribution. Let the *y*-axis represent the number of the count. Do the individual counts tend to be distributed uniformly, or are some values more likely to turn up than others? How are these values related to the average c/m obtained earlier? Is the graph symmetrical, or are values greater at one side of the graph than at the other?
2. You might like to keep a record of background count over a period of days or weeks, to see whether or not it remains constant. If it does not, suggest reasons for the variation.

INVESTIGATION

14

Shielding from Radiation

Introduction

Protection from ionizing radiation is provided by shielding. Lead, concrete, and water are examples of materials used for shielding. However, any material, even air, can be effective as a shield if you have a thick enough slice of it. Without the miles of air surrounding the earth, the background count due to cosmic rays would probably be high enough to be dangerous.

How does the amount of radiation that gets through a shield vary as the shield is made thicker? Certainly it should decrease, but is the decrease in amount of radiation the same whenever you add a certain thickness of shield? If the answer to this question is "Yes," then you would get a straight-line graph when you plot thickness against radiation. Your problem is to find whether the relationship is graphed as a straight line or as a curve.

Equipment

G-M counter with a dial that registers counts per minute (c/m) or milliroentgens per hour (mr/hr); or a scaler that records counts for a preset time; luminous-dial watch; cardboard backing from a school pad.

Procedure

STEP 1 You will want to measure the radiation from the face of a luminous-dial watch either in c/m or in some other measure. If your counter has a movable pointer on a scale, it may read in milliroentgens per hour (mr/hr). A *roentgen* is a measure of the ability of radiation to ionize air. Either c/m or mr/hr can be used to tell how much radiation is reaching the G-M tube. Examine your counter to determine the unit in which you will measure radiation. Record in your *Data Book* the type of counter used, including the model number.

STEP 2 Read instructions for operating the counter and set it into operation.

STEP 3 The plan is to keep the watch dial and the G-M tube a fixed distance apart and then to determine the amount of radiation (R) reaching the tube when the shielding is 0, 1, 2, 3, 4, 5 or more thicknesses (t) of cardboard. Finding the proper fixed distance differs for a counter with a movable pointer and for a scaler.

If you use a counter with a movable pointer, notice that there are several ranges. Start with the highest range (probably X 100, which means that whatever the scale says must be multiplied by 100). Bring the watch near the window of the G-M tube and note how close it must be to send the needle nearly across the scale. If there is less than an inch of space between the watch and the G-M tube, use a lower scale. Set the watch and G-M tube in such a position that **a)** the needle deflects nearly across the dial; **b)** the needle does not fluctuate wildly (although it will fluctuate more than you might wish it would); and **c)** there is at least an inch of space between the watch and the G-M tube. Record the scale setting you are using.

If you use a scaler, set the watch at a distance between 1 and 2 inches from the window in the G-M tube.

Once you have found the proper fixed distance, do not change the distance between the watch and the G-M tube during the investigation.

STEP 4 Set up a data sheet and make your measurements. Note the following:

If you are using a counter with a movable pointer, the pointer will fluctuate. Make the best estimate you can of the average around which the pointer is fluctuating. After you have recorded measurements for all of the different thicknesses of cardboard, make a second set of measurements to improve the accuracy of the estimate. Calculate and record the average of the two readings.

If you are using a scaler, experiment a bit to decide how long it should count to give you a reliable figure.

STEP 5 Graph your data. Decide which variable (R or t) is the independent variable and put it on the x-axis.

Discussion

1. Is the relationship between thickness of the shielding and the amount of radiation that gets through the shielding a straight-line one? Before answering this question, hold the graph in a horizontal position slightly below the eye level and sight along the data points. Are the points distributed at random along what seems to be a straight line, or is there a regular curvature?
2. In order to get the true value for the radiation reaching the counter from the watch dial, you should subtract the background reading from the counter reading. Why was it not necessary to do this in this experiment?
3. Why does the movable pointer fluctuate?
4. When you did Investigation 13, you found that it takes a long time to get a reliable background count. Why does it take less time to get a reliable count when the amount of radiation is much greater, as is the case with the watch dial?
5. With some scalers, you can set the instrument to show the length of time it takes to count a certain number of entering particles (256, for example). How might this sometimes be an advantage over using the instrument to show the number of counts in 1.00 minute?
6. Do your data give you any clues to the amount of shielding necessary to cut out all radiation?

For Further Investigation

1. Attempt to determine the equation that describes the curve obtained when you graphed your data. Use the method described under *For Further Investigation* on page 18. Be sure that the variable you change is the dependent one. When you succeed in making a straight-line graph, its equation will be in the form $y = mx + k$, where y is the dependent variable (in its changed form), m is the slope of the line, x is the independent variable, and k is the y-value where the line crosses the axis.
2. If the thickness of a shield were measured in meters or centimeters or feet, it would standardize the procedure to a certain extent. However, the shielding effect of 1 cm of lead is quite different from the shielding effect of 1 cm of paper. In order to compare the effect of placing equal masses of shielding between a radiation source and a counter, physicists invented a new kind of measure of thickness, the milligram per square centimeter (mg/cm^2). Suppose you have a shield that is 1 mm thick. You mark out a square on the front of the shield that has 1 cm on a side. Now you cut a square through the shield, from front to back, that has the 1 cm^2 square at one end and another 1 cm^2 square at the other end. If the chunk weighs 1 mg, then the thickness of the shield is 1 mg/cm^2. If another shield, also 1 mm thick, is treated in the same way and the chunk weighs 5 mg, then its thickness (for radiation shield purposes) is 5 mg/cm^2.

   Repeat the investigation of shielding, using a variety of materials. Try such things as sheets of aluminum foil, flat sheets of other metals, and glass. In each case, use a material for which it is possible for you to determine the mass of a piece with a surface area of 1.00 cm^2. Of course, you can do this by weighing a rectangular piece of the material and dividing by the area. Graph R against thickness in mg/cm^2, with values for all of the different materials recorded on the same graph. Discuss the results.

The Addition of Concurrent Forces

15

Introduction

If two or more forces act on the same object, what is the result? Here are three examples. Guess at the answers. There is no penalty for incorrect guesses. The answer you give in each case is called the "resultant." **a)** Two boys pull on a cart, as shown in Fig. 15–1a. What is the total force? Give both magnitude and direction. **b)** The two boys pull, as shown in Fig. 15–1b. What is the total force? Give both magnitude and direction. **c)** The two boys pull, as shown in Fig. 15–1c. What is the total force? You may not be able to answer this question as precisely as the others. Make a reasonable guess about magnitude and direction.

The first two of these situations are easy, but the third one is more complicated. It is the purpose of this investigation to explore the third situation.

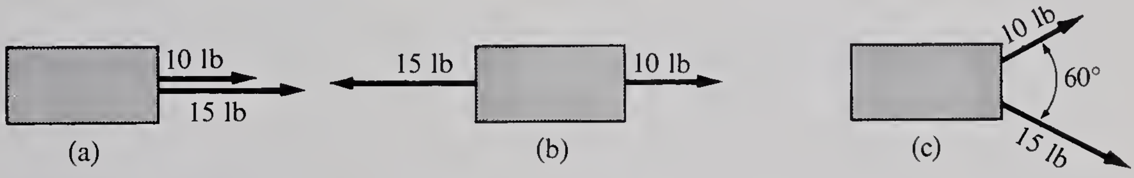


Fig. 15–1 What is the resultant in each of these situations?

Equipment

For each group of students: 2 spring balances; nylon fish line; known weight; support for suspending the apparatus of Fig. 15–3.

Procedure

Before you start your investigation, answer the questions in this section and be sure your answers are correct.

a) For Fig. 15–1a you probably wrote that the total force is 25 lb to the right. If the two boys stop pulling, but another boy takes their place and pulls to the right with a single force of 25 lb, the cart will move in exactly the same way as when the two boys were on the job. The **resultant** is the single force that produces the same effect as the combination of the other two forces. In Fig. 15–1b what are the magnitude and direction of the resultant?

b) Now go back to the situation of Fig. 15–1a, with two boys pulling on the cart. Suppose that you want to balance the situation by adding a third force that will exactly cancel out the other two. You could have a third boy pull toward the left with a force of 25 lb. This force is called the **equilibrant.** The equilibrant is equal in size to the resultant, but opposite in direction. In Fig. 15–1b what are the magnitude and direction of the equilibrant?

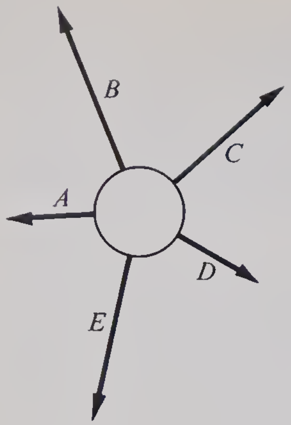


Fig. 15–2 The ring is in equilibrium when pulled by the five forces shown here.

c) When you add an equilibrant to a group of forces acting on an object, then the object is in **equilibrium.** In the case of the boys and the cart, if a third boy supplies the equilibrant (25 lb to the left), the cart cannot start to move. When you have a group of forces acting on an object and the object does not move, any one of the forces is the equilibrant of all the other forces. For example, suppose that five forces are pulling on a ring, as shown in Fig. 15–2, and the ring does not move. The length of each arrow is proportional to the magnitude of the force. Any one of these forces can be called the equilibrant of the other four. *A* is the equilibrant of *B*, *C*, *D*, and *E*. What is the equilibrant of *E*, *A*, *B*, and *C*?

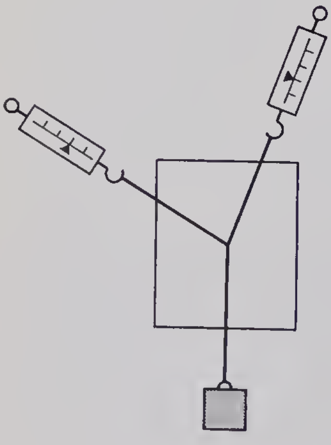
d) Trace Fig. 15–2 and draw, on the diagram, the resultant of *A*, *C*, *D*, and *E* all combined. Label it. Reread the statement about the equilibrant if necessary before you make your drawing.

e) Any quantity that has both magnitude and direction is called a *vector*. Vectors are represented in drawings by arrows. The arrow is drawn in the direction of the vector, and its length represents the magnitude of the vector. In Fig. 15–2 which vector has the greatest magnitude? Which has the smallest magnitude?

f) The forces illustrated in Fig. 15–2 are called *concurrent forces* because if you extend the lines of the vectors they all intersect at the same point. Extend the lines in your copy of Fig. 15–2 to show that the forces are concurrent. Now show that the forces in Fig. 15–1c are concurrent.

STEP 1 Support a known weight with two strings, each connected to a spring balance, as shown in Fig. 15–3. Do not have both balances suspended at the same height.

Fig. 15–3 Set up your equipment in this manner.



STEP 2 At the point where the strings are attached to each other, three forces are acting. The directions of the forces are the same as the directions of the strings. Put a dot near the center of a blank sheet of paper. Hold the paper behind the three strings, with the dot exactly behind the point where the strings intersect. Make a dot below the outer edge of each string. Take the paper down and draw very lightly in pencil the three lines from the point of intersection. Hold up the paper behind the apparatus again to see whether the lines are correctly drawn. If they are not, correct them, and again check your accuracy. The directions must be very accurately located.

STEP 3 The size of the downward force is equal to the size of the known weight. The other forces can be read from the spring balances. Record the size of each force on the proper line in your diagram.

STEP 4 Adopt a convenient scale of distances (for example, 1 cm = 5 g). Select a scale that will use most of the available paper without running off it at any point. Using this scale, make each of the lines on your paper the proper length. At the outer end of each line put an arrowhead, as was done in Fig. 15–2.

STEP 5 Choose one of the forces to be equilibrant of the other two. Label it "Equilibrant." Then draw the line that represents the resultant of the other two. Label it "Resultant."

STEP 6 Draw lines from the outer tip of the resultant to the tips of the other two forces.

STEP 7 Place another paper behind your apparatus and repeat the procedure with a different force as the equilibrant.

STEP 8 Make a scale drawing to find the resultant for Fig. 15–1c. Compare the answer with your original guess.

Discussion

1. How does the direction of the resultant compare with the directions of the two forces of which it is the resultant?
2. What kind of geometrical figure did you draw in Step 6? In this figure what geometrical name is given to the line that represents the resultant?
3. How can the size and direction of the resultant of two concurrent forces be found by using a scale drawing?
4. How do you know that the directions of the forces correspond to the directions of the strings?
5. Would it be satisfactory to compute the lengths of the supporting force vectors from the lengths of the strings rather than from the readings of the spring balances? Give reasons for your answer.
6. What is the advantage of selecting a scale of distances as large as the paper permits?
7. When two or more forces are acting in the same or in opposite directions, they can be added or subtracted according to the familiar rules of arithmetic. Is this special case an exception to the rules for adding forces that you have discovered in this experiment? Give reasons for your answer.
8. Why must every stationary object either have no force acting on it or a minimum of two forces?
9. If two forces act at right angles to each other, they can be added by using a scale drawing, as you have done in this experiment. From your knowledge of geometry, can you think of any other way to perform this addition? Describe your method.
10. How could you add four forces acting at the same point, as shown in Fig. 15–4 on the next page? Modify the method you used for two vectors.
11. Vectors can also be added by placing them "head to tail" in chain fashion. This method is illustrated in Fig. 15–5. Can you show that this method produces the same result as the method you used in the preceding question? Which method is easier when you have more than two vectors to be added, the parallelogram method or the "head-to-

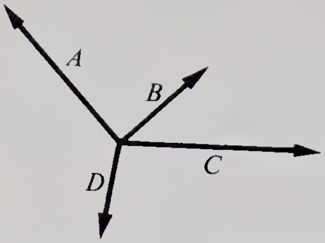


Fig. 15–4 How can you find the resultant of these forces?

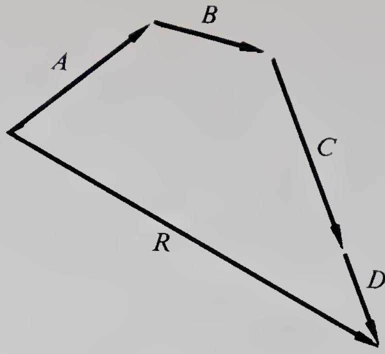


Fig. 15–5 Another way to add vectors.

tail" method? For either method, does the order in which you take the vectors make any difference in the result?

For Further Investigation

Repeat the experiment with three or four supporting strings instead of two.

INVESTIGATION

16

Equilibrium with Parallel Forces

Introduction

If two men pull with equal force at opposite sides of a box, as shown in Fig. 16–1**a**, the box does not start to move because the forces are in equilibrium. However, if they pull at the corners, as shown in Fig. 16–1**b**, the box will rotate until it is in the position of Fig. 16–1**c**. In all three cases the force to the right is exactly equal to the force to the left. Why is there equilibrium in **a** and **c**, but not in **b**? It is the purpose of this investigation to explore situations in which unbalanced forces produce rotation.

In Investigation 15 you dealt with equilibrium when the forces were concurrent. In **a** and **c** of Fig. 16–1, the forces are concurrent; in **b** they are parallel. A good way to investigate parallel forces is to hang objects from a suspended meter stick. Since the earth pulls all of

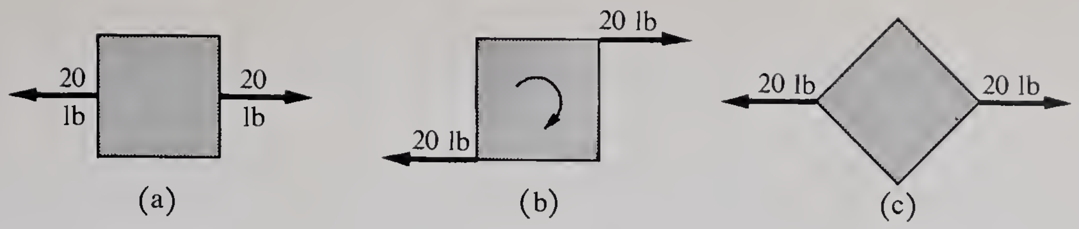


Fig. 16–1 The two 20-lb forces produce equilibrium in **a** and **c**, but not in **b**.

the objects downward, the weights are parallel forces. In the first part of the experiment you will be following some rather exact instructions about what weights to use, how to hang them, and how to record the data. Then, examining the data, you will look for a law that tells how equilibrium can be produced by parallel forces. Next, you will set up a hypothesis about the law. When you have a hypothesis, you must test it in new situations to decide whether to accept it or reject it. Therefore the later parts of the experiment will consist of experiments you yourself design to test your hypothesis.

Equipment

Meter stick; suspension clamp for meter stick if available; fish line; sticky tape; set of weights; an object of unknown weight that can be easily suspended; laboratory balance.

A. EQUILIBRIUM WITH TWO PARALLEL FORCES

Procedure

STEP 1 Suspend a meter stick by a suspension clamp so that it balances. If a suspension clamp is not available, use a loop of fine cord and tape it in position on the meter stick. The meter stick may not balance at the exact center. Record in your *Data Book* to the nearest 0.01 cm the position at which the meter stick does balance. By suspending the meter stick at its balance point, you arrange things so that the weight of the meter stick itself cannot be a cause of rotation and can therefore be ignored during the rest of the experiment.

You are now going to hang weights at various places along the meter stick to produce balance. Each time you produce balance, you must record, to the nearest 0.01 cm, the position of each weight. You can keep this record in chart form, or you can make a simplified drawing of the meter stick and record your findings there, as shown in Fig. 16–2.

STEP 2 Hang a 100-gf weight 40.0 cm to the right of the balance point and tape the cord in place. This weight causes the meter stick to rotate in a clockwise direction. Balance it by suspending a second 100-gf weight to the left of the balance point. Record the position of the second weight on the data sheet and calculate its distance from the balance point. This distance is called the lever arm.

STEP 3 Replace the 100-gf weight on the right by a 50-gf weight taped in the same position. The stick will turn in a counterclockwise direction. Move the 100-gf weight on the left

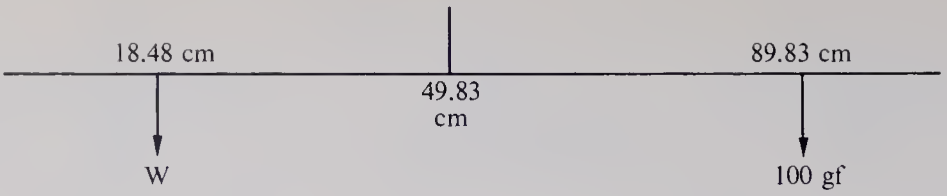


Fig. 16–2 Data can be recorded by making diagrams like this one.

until the stick again balances. Record the positions of the weights on your data sheet and calculate the lever arm for the 100-gf weight.

STEP 4 Replace the 100-gf weight on the right by a 25-gf weight taped in the same position. Move the left-hand weight until the stick balances. Record the positions of the weights on the data sheet and calculate the lever arm for the 100-gf weight.

STEP 5 Examine your data for signs of a law describing the balanced situations that you have been investigating. State your hypothesis about the law in your *Data Book* and label it "Hypothesis." Test the hypothesis by setting weights in new positions that should produce balance if your hypothesis is true. Record the data below the statement of the hypothesis to show how you tested the hypothesis. Below the data state whether or not the weights did produce balance.

A good scientist keeps a record of his failures as well as his successes because they help him to make better hypotheses. In 1957 C. N. Lee and T. D. Yang won a Nobel Prize in physics for an experiment that demonstrated that a hypothesis that scientists had thought to be a good one was really not true. (The hypothesis had to do with conservation of parity, a concept used in advanced nuclear physics.) It is possible that your first hypothesis may not pass the test. Even so, it should be recorded as part of your report. Make several tests, until you are sure that you have the correct law. Use additional pages if necessary, to make a record of all attempts.

Discussion

What is the law for equilibrium with two parallel forces? Using data from the experiments you set up to test the hypothesis, show the calculations used to support your conclusion.

B. EQUILIBRIUM WITH MORE THAN TWO PARALLEL FORCES

Procedure

STEP 1 Invent a way to apply your law when you have more than two weights. For example, you might have a 100-gf weight on the left and two weights on the right, one of 50 gf and the other of 25 gf. You may either set up a hypothesis about this and then test it, or put the weights on the meter stick and move them about until they balance, and then try to figure out the law. When you think you know the law, test it with a number of different arrangements of weights. Record all of your tests on a data sheet.

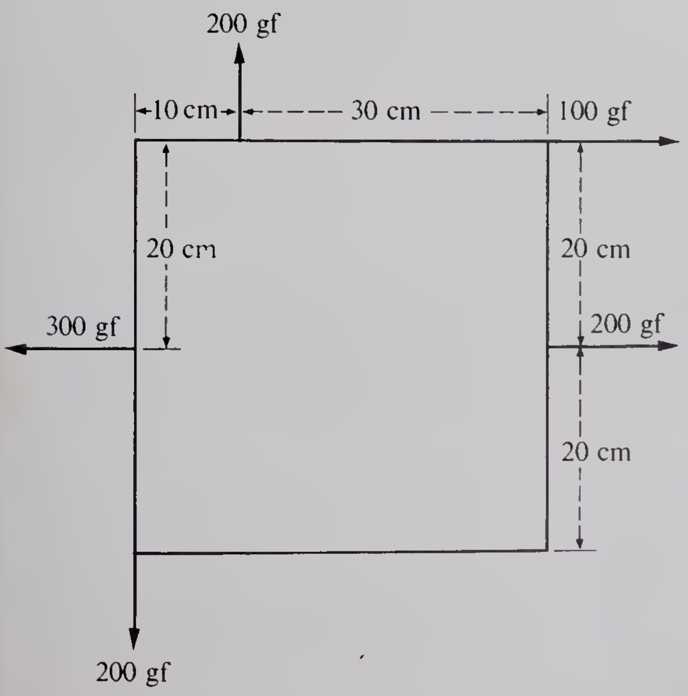
STEP 2 Use the law to weigh an object of unknown weight. Do it twice, using different known weights. In your *Data Book* describe the method you used. Set up the data neatly and show the results. Average the two answers. Weigh the unknown on the laboratory balance.

Calculate the percent of difference between the average weight obtained by using the meter stick and the weight obtained by using the laboratory balance. This is not the same as percent of error, since you have no way of knowing which weighing is more accurate. See Appendix 4 for instructions about percent of difference.

Discussion

1. The product of a force times its lever arm is called the **moment** of the force. The law for equilibrium of parallel forces is called the **law of moments.** State this law in such a way that it applies to more than two forces. Show the calculations used to support your conclusion.
2. The law of moments states only one of the conditions necessary for equilibrium with parallel forces. It is also necessary that the resultant of the forces themselves be zero, just as in the case of concurrent forces. When you had two 100-gf weights on the meter stick, they provided a total downward force of 200 gf. Since there was equilibrium, there must have been an upward force of 200 gf somewhere in the system. How was this upward force applied to the meter stick?
3. How could you measure the upward force to see whether or not it was equal to 200 gf?
4. If you found the upward force to be 270 gf, how would you account for this discovery?
5. How could you check your answer to Discussion Question 4?

Fig. 16–3 This square object is in equilibrium. Can you prove it?



For Further Investigation

The law of moments also applies to nonconcurrent forces that are not all parallel to each other. For example, the object shown in Fig. 16–3 is in equilibrium. See whether or not you can apply the law of moments in such a way as to prove that the object is in equilibrium. To do this, you may take any convenient point (one of the corners, for example) as the point of rotation. You may also extend the arrow that indicates a force, in order to find the lever arm. A lever arm is always drawn from the point of rotation perpendicular to the line along which the force acts.

INVESTIGATION

17

Center of Gravity

Introduction

Suppose you are holding a stone in an outstretched hand. How can you calculate the moment of its weight about your elbow? You could find the weight of the stone easily enough, but to determine the lever arm is a more difficult problem. Perhaps the stone is 10 cm across. Each part of the stone has a different lever arm. You might imagine the stone being sliced into thin pieces (Fig. 17–1). The first slice weighs 5 gf and is 18.0 cm from your elbow; the second slice weighs 12 gf and is 18.1 cm from your elbow, and so on. Even if you could slice up the stone in this manner, it would be a most difficult way in which to solve the problem, so difficult that no one in his right mind would bother with it.

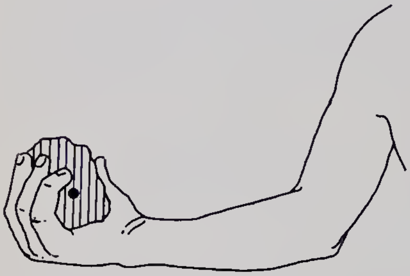


Fig. 17–1 How can the moment caused by the weight of this rock be determined?

Fortunately there is an easier way. If you can locate the center of gravity of the object, you can pretend that all of its weight is concentrated at that one point. In Fig. 17–1 the center of gravity of the stone is indicated by a dot, which is 20.0 cm from the elbow. If the stone weighs 250 gf, the moment about the elbow is 250 gf × 20.0 cm, or 5.00×10^3 gf·cm.

It is the purpose of this investigation to show you how the center of gravity of a simple object may be located and to help you to understand how the center of gravity is related to equilibrium.

Equipment

A piece of cardboard (the backing of a school composition pad, for example); 2 ft of thin string; a nail about 3 in. long; something to tie to the string that is heavy enough to make the string hang straight down; other materials used in Investigation 16.

Procedure

You are looking for a way to locate the center of gravity of an object when it is in equilibrium. It is easier to locate the center of gravity of a flat object than of a stone. Therefore you will work with a sheet of cardboard in this experiment. However, what you learn about center of gravity will apply also to objects of other shapes.

STEP 1 Tie a weight to one end of a piece of string, and tie a small loop in the other end, so that a nail can be slipped through the loop.

STEP 2 Cut the cardboard into an irregular shape and punch holes through it at various places, as in Fig. 17–2. The holes should be slightly (but not much) bigger than the nail.

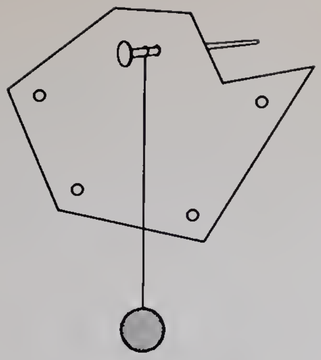


Fig. 17–2 The first step in finding the center of gravity of a piece of cardboard.

STEP 3 Hold the nail horizontally. Hang the cardboard on it by one of the holes, and hang the weighted string on the nail (Fig. 17–2). The string will hang vertically downward beside the cardboard. While one person holds the nail, another should mark the position of the string by making two pencil marks on the cardboard. Then, putting the cardboard on a table, use a ruler and pencil to draw (lightly) the line between the two dots. Using the same hole, hang the cardboard and string up again, to determine whether the line has been drawn accurately. If not, correct it. Repeat these steps with each of the holes in turn. What do you discover about the lines that you have drawn?

STEP 4 The point where the lines cross is the center of gravity of the cardboard. Punch a hole there (slightly bigger than the nail) and suspend the cardboard again from the nail. Be sure that the cardboard can be turned easily when the nail is in the hole. Turn the cardboard into various positions. Does it stay in position, or does it rotate when you take your hand away?

STEP 5 Suspend the cardboard from one of the other holes and try rotating it. Does it stay in position, or does it rotate?

STEP 6 Find the center of gravity of a pencil by slipping it through a loop of string that is slightly larger than the pencil and suspending it from above. Then balance the pencil horizontally on one of your fingers. Where is the center of gravity in relation to your finger when the pencil is balanced on one finger?

STEP 7 Balance the pencil horizontally on two fingers held about an inch apart. Where is the center of gravity in relation to your fingers?

STEP 8 Tie strings through two holes in the cardboard (Fig. 17–3). Suspend the cardboard by holding one string in each hand. Where is the center of gravity in relation to the two strings?

Discussion

1. What is the equilibrium position of an object supported from above **a)** by a single support? **b)** By two supports?
2. What is the equilibrium position of an object supported from below **a)** by a single support? **b)** By two supports?

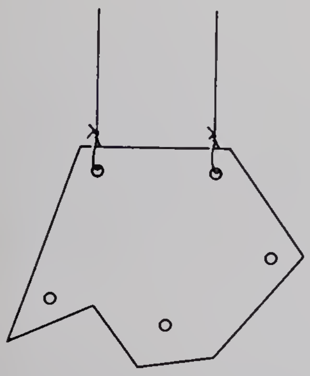


Fig. 17–3 The center of gravity of a piece of cardboard in relation to two supporting strings.

3. What is the equilibrium position of an object supported at its center of gravity?
4. Show that your answers to the three questions above agree with the law of moments.
5. How could you get an approximate idea of the location of the center of gravity of a stone?
6. Stand with your back to a wall and with your heels against the wall. Have someone place a book on the floor about a foot in front of you. Try to pick up the book. Explain what happens.
7. Where is the center of gravity of a doughnut? Check your response by cutting a flat doughnut shape out of cardboard, using the procedure of this experiment.

For Further Investigation

It is possible to weigh a meter stick by suspending it and hanging only one known weight upon it. Devise a method for doing this. Describe your method and show your results. Check the weight by weighing the meter stick on a laboratory balance. Calculate the percent of difference in the two methods of weighing.

INVESTIGATION

18

The Force of Friction

Introduction

If you give a push to a block of wood, it slides along the floor and comes to rest. You learned in Investigation 1 and in your study of Newton's laws that the slowing down is due to an unbalanced force, the force of friction. You also learned in that investigation that the force of friction is not always the same. It was less when the cart was right side up than when it was upside down; less still for a rolling ball. It is the purpose of this investigation to explore some of the factors that influence the size of the force of friction.

Equipment

For each group of students: horizontal table; board; block; additional weights to add to block.

Procedure

Before you start your investigation, answer the following questions:

a) If you are pulling an object in a straight line along a table top, in what direction does the force of friction act?

b) Suppose that you are using a string to pull the object. If the object moves with uniform velocity, how does the force of friction compare with the tension in the string?

c) Figure 18–1 shows a way in which you can apply a force to a block. If the weight of the hanger and its load is 100 gf and the block starts without being pushed and speeds up as it goes, what do you know about the force of friction?

d) If the weight of the hanger and its load is 90 gf and the block does not start without being pushed, but speeds up after it gets started, what do you know about the force of friction?

e) If the weight of the hanger and its load is 80 gf and the block starts only if you push it and comes to rest soon after you stop pushing, what do you conclude about the force of friction?

f) If the weight of the hanger and its load is exactly equal to the force of friction, how should the block behave?

g) In Fig. 18–1 the string is shown parallel to the table. Would it make a difference if the string were not parallel? Why?

h) One factor that might affect the size of the force of friction is the size of the force holding the two surfaces together. This force is called the normal force because it is perpendicular to the surfaces. How could you measure the normal force shown in Fig. 18–1?

STEP 1 Set up the apparatus, as shown in Fig. 18–1.

STEP 2 Set up a data chart for recording the normal force and the force of friction for five or more different loads on the block. Record the kind of material of the block and board. Make the measurements and record them.

STEP 3 If it were possible to reduce the normal force to zero, what should be the force of friction? Record this on the data chart.

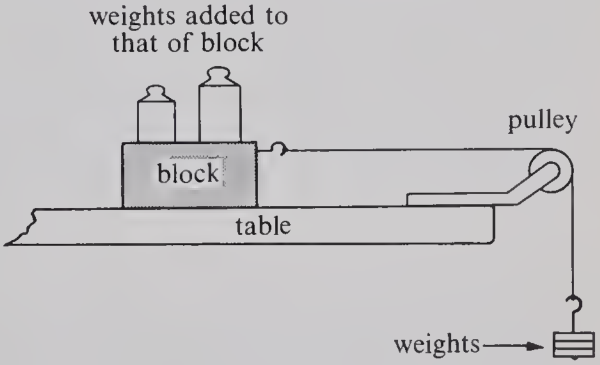


Fig. 18–1 How to measure frictional forces and the coefficient of friction.

STEP 4 Graph the data. There is one point from the data sheet through which the line on your graph must pass. Be sure you know which one it is.

STEP 5 List other factors that might influence the size of the force of friction. Investigate another factor from your list. Record data clearly, organize the observations in a graph, chart, etc., and report your conclusions. Different groups of students should investigate different factors. At the end, summarize not only what you have discovered, but also what others have learned.

Discussion

1. What appears to be the relationship between the force of friction and the normal force?
2. The coefficient of friction (k) is defined as

$$k = \frac{\text{force of friction}}{\text{normal force}}$$

   From your graph determine the coefficient of friction for the block and table. Show the method you used for your computation. In what units should the coefficient be expressed?
3. Compare your graph with those of Investigations 4 and 5. Discuss the degree of experimental error involved in the three situations. What are some sources of experimental error in the measurement of coefficient of friction? How reliable is your value for the coefficient? Could the measurement be made more reliable by other techniques?
4. Why is it better to use the graph for computation of coefficient of friction than to use the data directly from the data sheet?
5. How did the force required to start the block compare with the force required to keep it moving at a uniform velocity? Suggest hypotheses to account for the difference.

For Further Investigation

1. If you place your block on a board and then tilt the board, the block will slide down when you get the angle just right. In Fig. 18–2 the board has been raised to such a point that if you give the block a push, it will slide down the slope with a uniform velocity. By using the definition of coefficient of friction, your knowledge of force components, and the geometry of the situation, prove that

$$k = \tan A$$

2. Check the accuracy of the equation just derived by measuring the coefficient when the board is flat (by the method used in the first part of this experiment), and by computing the tangent of the angle when the block slides with uniform velocity.

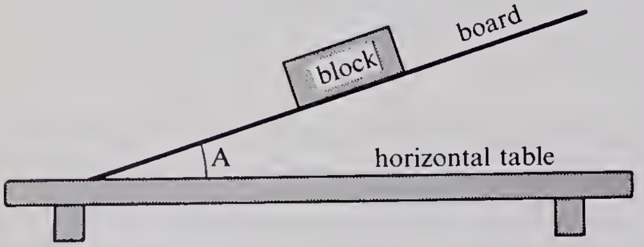


Fig. 18–2 Another way to measure coefficient of friction.

INVESTIGATION

19

Machines

Introduction

A machine is a mechanical device that makes it possible to do work more conveniently than if you did not have the machine. A machine has no energy supply of its own, so you must do work on it to get it to do work. The purpose of this experiment is to introduce you to the way in which certain simple machines operate. You will study the operation of one or more machines and report on their mechanical advantage and the efficiency.

Equipment

Machines such as inclined plane; pulleys; (singly and in groups); chain hoist (differential pulley); wheel and axle; jackscrew; weight hangers; weights and fish lines.

Procedure

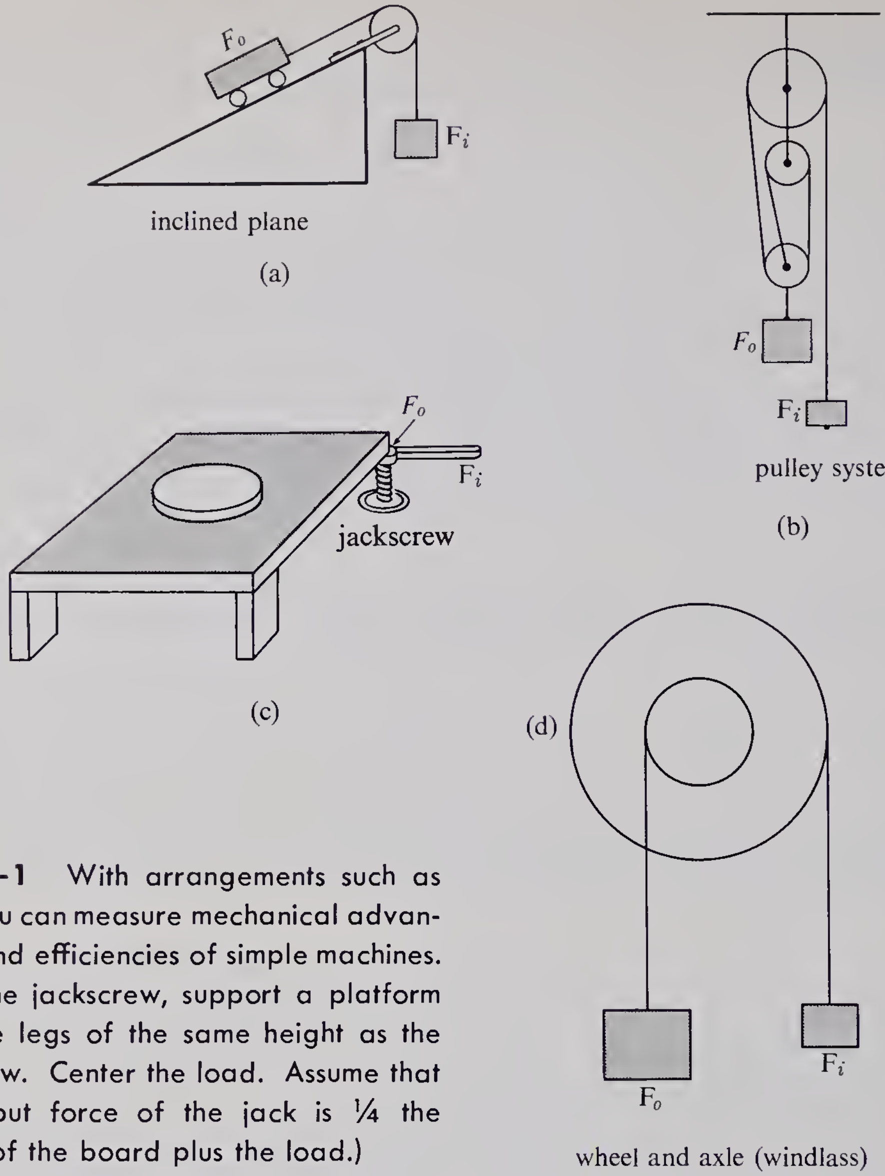
Before you start your investigations, read the following statement and answer the questions to see whether you understand the necessary definitions.

Assume that you use a force of 240 gf to push a 1200-gf load up an incline that is 40.0 cm long and is 5.0 cm higher at the upper end than at the lower end. Find each of the quantities defined below.

a) The **input force** F_i is the force exerted from the outside on the machine.
b) The **output force** F_o is the force that the machine works against. In this case it is the weight that is to be lifted.
c) The **work input** is the work done on the machine.
d) The **work output** is the work done by the machine.
e) The **actual mechanical advantage** (MA) is the ratio F_o/F_i.
f) The **ideal MA** is the ratio $\dfrac{\text{input distance}}{\text{output distance}}$.
g) The **efficiency** is the ratio $\dfrac{\text{work output}}{\text{work input}}$.

STEP 1 Figure 19–1, on the next page, shows ways in which various machines can be set up for testing. Examine your machine to see how you can measure input and output forces and input and output distances.

STEP 2 Set up a data sheet on which you will record the quantities to be measured and the quantities to be computed. Make measurements for at least 5 different loads on the machine. These loads should range from one that seems quite light to one that taxes the ability of the machine. Remember that you must record the force that keeps the load moving at a steady speed after it has started, not the force necessary to start it nor a force that accelerates it.



inclined plane

(a)

pulley system

(b)

jackscrew

(c)

(d)

wheel and axle (windlass)

Fig. 19-1 With arrangements such as these you can measure mechanical advantages and efficiencies of simple machines. (With the jackscrew, support a platform on three legs of the same height as the jackscrew. Center the load. Assume that the output force of the jack is ¼ the weight of the board plus the load.)

STEP 3 Calculate the actual and ideal mechanical advantages and the efficiency for each of the different loads.

Discussion

1. Is the efficiency of your machine approximately the same for different loads, or does it vary considerably? If it varies, does it change in a regular way? Can you explain why the efficiency remains approximately the same (if it does), or changes (if it does)?
2. Are some of the machines being tested in your laboratory more efficient than others? To answer this question, compare your results after testing several machines, or compare your results with those of other students. If certain kinds of machines seem to be more efficient than others, account for that fact. Is inefficiency a desirable characteristic in any of the machines tested in your laboratory?
3. Which is greater, ideal MA or actual MA? Will this always be true?

4. Compare your calculated values of efficiency with the ratio $\frac{\text{actual MA}}{\text{ideal MA}}$. What conclusion do you draw? Can you prove it mathematically?
5. Which machines tested in your laboratory have MA's that are easily changed? Which ones have fixed MA's?
6. Did your machine reduce the amount of work that had to be done to raise a load? Why was the machine useful?
7. Can one of the machines tested in your laboratory be so designed that it has an ideal MA less than 1? In what way might this be useful?
8. Can one of the machines tested in your laboratory be so designed that it has an ideal MA of 1? In what way might this be useful?
9. What are the basic causes of inefficiency in machines?

For Further Investigation

Set up the pulley system shown in Fig. 19–2 and test it. The results may surprise you. Account for them.

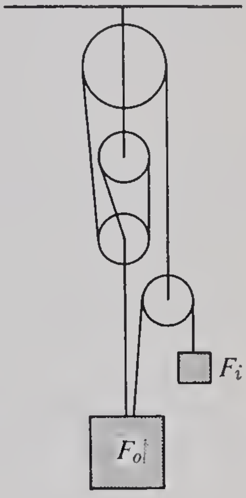


Fig. 19–2 A more complicated pulley system.

INVESTIGATION

20

Pressure in a Liquid

Introduction

If you walk across the kitchen floor in your stocking feet, carrying your ice skates in your hand, you do the floor no harm. If you put on the skates and continue your walk, you may make unsightly dents in the linoleum. The total force exerted in both cases is the same, but the pressure is different. **Pressure** is defined as force per unit of area. Its mathematical expression is shown below:

$$P = F/A$$

Pressure exists in liquids. Dams are thicker at the bottom because water pressure increases as the depth increases. Submarines and diving suits must be designed to withstand the increasing pressure at greater depths. It is the purpose of this experiment to discover just how the pressure exerted by a liquid is related to depth.

Equipment

For each group of students: glass tubing about 3 cm in diameter, 30 cm long; glass jar at least 30 cm deep; meter stick; lead shot; 10-gf and 20-gf brass weights that fit into glass tubing; rubber stopper that fits into the tubing with its top almost flush with the end of tubing, as shown in Fig. 10–1; laboratory balance.

Procedure

Your problem is to discover, with the use of the apparatus shown in Fig. 20–1, the relationship between the depth of water and the pressure it exerts. Note that the glass cylinder floats upright because it is weighted at the lower end.

Before you start your investigation, answer the following questions and have them checked for accuracy. Assume that the cylinder and its contents weigh 160 gf and that the area of the base of the cylinder is 8.0 cm^2.

a) Is the cylinder in equilibrium? How do you know?
b) What downward force acts on the cylinder?
c) What upward force acts on the cylinder?
d) How is the upward force supplied?
e) What is the water pressure on the stopper?
f) How can the depth of the water at the level of the stopper be determined?

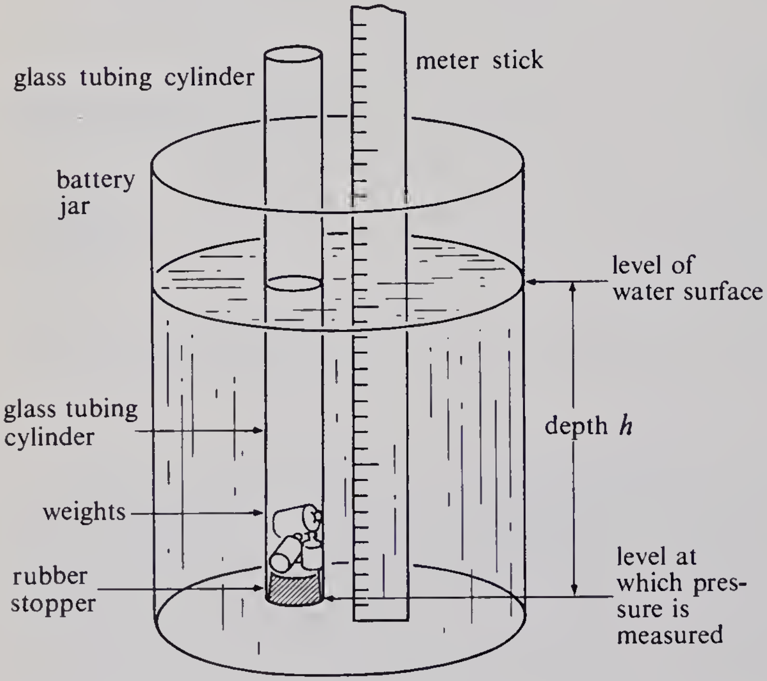


Fig. 20–1 A plugged and weighted cylinder provides a suitable means of determining liquid pressure.

STEP 1 Set up the apparatus, as shown in Fig. 20–1. Be sure the cylinder is very tightly stoppered. In order to make it float upright without tipping, you will have to add weight to it. Use shot or small brass weights and add as little weight as possible.

STEP 2 During the course of the experiment you will change the depth of the cylinder by adding 10-gf or 20-gf weights. You should make measurements for at least five different depths. Decide what you need to measure to calculate the depth (*h*) and the pressure (*P*) each time. Set up a data chart on which to record the quantities to be measured or computed. Be sure to state the units in which each quantity is measured. Let the chart have 2 extra columns to be used later.

STEP 3 Make the measurements and record the data. If the depth were zero, what would be the water pressure? Add these values to the data sheet.

STEP 4 From the depth and diameter of the cylinder, calculate the volume of water displaced by the cylinder for each depth. Record this in one of the extra data-sheet columns. From the fact that the weight density (d_w) of water is 1.00 gf/cm^3, calculate the weight of the displaced water. Record your answers in the other extra column.

Discussion

1. Compare the numerical part of the depth (*h*) that you measured each time with the numerical value of the pressure (*P*) at that depth. Within the limits of experimental error, what seems to be the relationship? Compare the units for *P* and *h*. Keeping in mind that the weight density (d_w) of water is 1.00 gf/cm^3, write an equation that would express the relationship between *P*, *h*, and d_w that would be correct both numerically and with respect to the units.
2. Compare the weight of the displaced water with the weight of the cylinder and its contents each time. Allowing for a certain amount of experimental error, what seems to be the relationship? What generalization can you make about the weight of a floating object and the weight of the water it displaces?
3. The upward force supplied by the water is called the **buoyant force** of the water. Compare the buoyant force acting on a floating object with the weight of water displaced by the object.
4. The apparatus used in this experiment does not provide a high degree of accuracy of measurement. What are some of the sources of error? How might the equipment be improved so that these errors would be lessened?
5. In English units the weight density of water is 62.4 lb/ft^3. What is the pressure at a depth of 10.0 ft? The weight density of a certain oil is 0.93 gf/cm^3. What would be the pressure in this oil at a depth of 100 cm?
6. Gases also exert pressure. The pressure of the atmosphere is often measured in centimeters of height of a mercury barometer. The higher you go, the lower the pressure, as indicated by the table at the right. In what way does the variation of atmospheric pressure with your location in the atmosphere resemble the variation of pressure in a liquid? In what way is it different? Account for the similarities and differences.

Elevation above sea level (km)	Pressure (cm of mercury)
0	76
2	60
4	47
6	36
8	27
10	21

7. If you had filled the jar in your investigation with oil with a density of 0.8 gf/cm^3, would the cylinder have floated at a higher level, at a lower level, or at the same level as with water? Give reasons for your answer.
8. A wooden cube with an edge 10 cm long weighs 700 gf. How much of the cube will float above water?
9. Some sea animals live at a depth of a mile or more in the ocean. Why are they not crushed by the force due to the pressure of the water? Why does such a fish explode if it is suddenly brought to the surface?
10. In this investigation you measured only the pressure due to the water. Actually there was atmospheric pressure in addition to that of the water. When the end of the cylinder was at a depth of 20 cm, there was a pressure of 20 gf/cm^2 due to the water, plus a pressure of approximately 1030 gf/cm^2 due to the atmosphere, making a total pressure on the stopper of about 1050 gf/cm^2. If the stopper had an area of 8 cm^2, this would produce a total upward force of more that 8000 gf on the cylinder. Why does this force not blow the cylinder out of the water?

For Further Investigation

1. Suppose you put into the water a stone instead of the hollow glass cylinder. It would not float. In this case would there be a buoyant force on the stone? Use your answer to this question as a hypothesis, and perform a simple experiment to test the hypothesis. Report the results.
2. The weight of the floating glass cylinder of your experiment may be considered to act at its center of gravity. The upward buoyant force of the displaced water may be considered to act at the center of gravity of the column of water. What must be the relative positions of the two centers of gravity for the cylinder to be in stable equilibrium?

INVESTIGATION

21

Buoyant Force

Introduction

You have probably noticed when you have been in swimming that it is easier to lift a rock that is under water than to lift the same rock when it is out of the water. The apparent loss of weight of an object immersed in a fluid comes about because the fluid helps to support the object; the supporting force is called the **buoyant force** of the fluid. The purpose of this investigation is to study the size of the buoyant force acting on an object immersed in water.

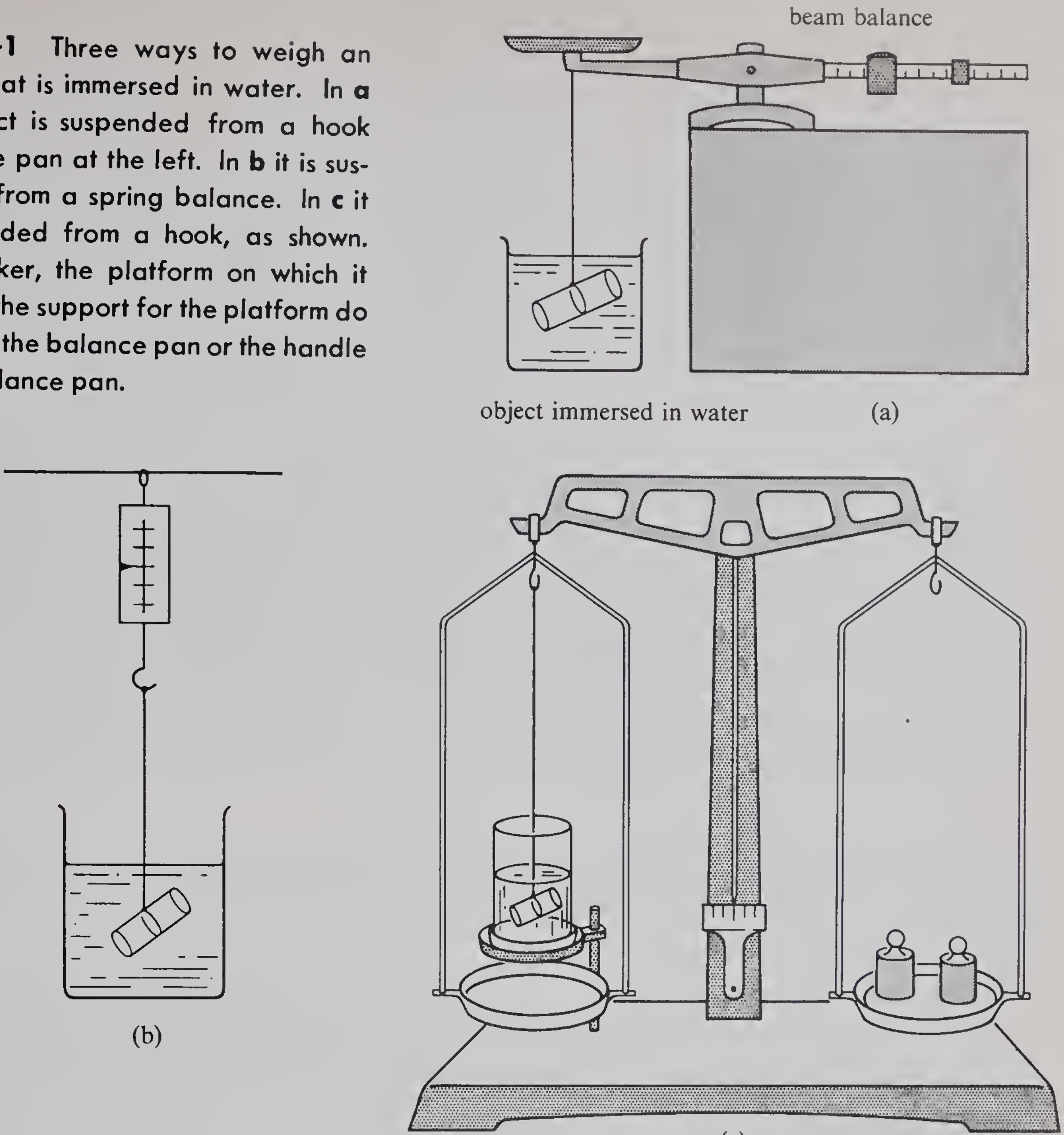


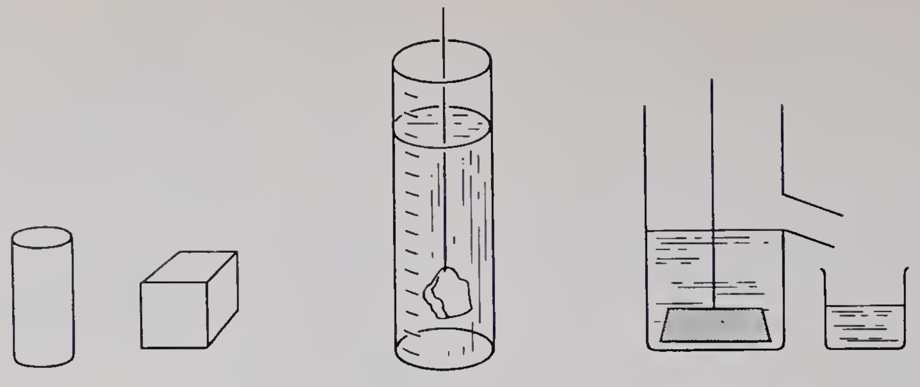
Fig. 21–1 Three ways to weigh an object that is immersed in water. In **a** the object is suspended from a hook under the pan at the left. In **b** it is suspended from a spring balance. In **c** it is suspended from a hook, as shown. The beaker, the platform on which it sits, and the support for the platform do not touch the balance pan or the handle of the balance pan.

Equipment

Heavier-than-water objects that can be suspended from balances, as shown in Fig. 21–1; balances (one or more of the types shown in Fig. 21–1); volume-measuring equipment (one or more of the types shown in Fig. 21–2).

Procedure

Figure 21–1 shows three methods for weighing an object in air and in water. Suppose that you have done the weighing and find that your object weighs 80 gf in air and 60 gf when immersed in water. The apparent loss of weight is 20 gf, which is 25% of the weight in air. Possibly all objects immersed in water will seem to lose 25% of their weight. Another possibility is that the loss is related to the volume of the object. Figure 21–2 shows several methods for finding the volume of the object. Your problem is to discover how the buoyant force on an object immersed in water is related to its weight in air and to its volume.



(a) (b) (c)

Fig. 21–2 Three methods for determining the volume of an object. **a.** If the object is regular in shape, measure its dimensions and calculate its volume. **b.** If the object is irregular in shape, partly fill a graduate with water and find the volume of the object by determining how much the water rises in the graduate when the object is immersed. **c.** If the object will not fit into a graduate, fill an overflow can with water until it runs out of the spout. When the water stops running, place a catch bucket under the spout and put the object in the water (without splashing). From the weights of the empty catch bucket and the catch bucket with the overflow water, you can find the weight of water displaced and thus the volume of the object.

STEP 1 Examine the apparatus available in your laboratory and the various objects you can weigh, and decide how you will obtain the weights and volumes.

STEP 2 Set up a data sheet.

STEP 3 Make the measurements.

STEP 4 Make any computations necessary for answering the first three questions of the *Discussion.* Show clearly on the data sheet what computations you made and how they are related to the data.

STEP 5 Make a chart listing the information needed to answer the first three Discussion questions, and enter in the chart your own data and data from the other investigators in your laboratory.

Discussion

1. Is the buoyant force on an object immersed in water related to the weight of the object in air? If your answer is "Yes," how is it related? If the answer is "No," give reasons for your answer.
2. Is the buoyant force on an object immersed in water related to the volume of the object? If your answer is "Yes," how is it related?
3. Is the buoyant force on an object immersed in water related to the weight of the water displaced by the object? If your answer is "Yes," how is it related?
4. Similar experiments with other liquids and with gases show that the relationship you have discovered applies to all fluids (liquids and gases). A balloon filled with helium, for example, rises because the buoyant force supplied by the air is greater than the weight

of the balloon and its contents. Write your conclusion in a generalized form that applies to fluids of all kinds.

5. Undoubtedly your experimental results contain measurement error. With the kind of balance that you used for the weighing, what is the largest error that you think is likely if you do a careful job? What do you think is the largest error likely in your measurement of volume? What is the largest amount by which any of the data disagree with your conclusions in this experiment? Could this disagreement be accounted for by the estimates you have just made of the likely errors of measurement?
6. Why was it important to compare your results with those of other students?
7. By using the discovery you have made in this experiment, it is possible to calculate the specific gravity of your object from its weight in air and apparent weight in water. Do this and explain your method clearly.
8. Because of the buoyant force supplied by the air, the weight of an object in air is not its true weight. Would the true weight be greater or less? Give reasons for your answer.
9. If you performed Investigation 7, show that the conclusion in that experiment about buoyant force is a special case of the conclusion in this investigation.

INVESTIGATION

22

The Magnetic Field of a Permanent Magnet

Introduction

If you hold a small permanent magnet a millimeter or so from an iron tack, you find that the tack is attracted even when the magnet is not touching it. It is customary to think of a magnet as being surrounded by a magnetic field that stretches out to infinity. It is the field that exerts the force on the tack. At any point in the field the force is exerted in a particular direction. In this investigation you will map the direction of the magnetic field around a bar magnet.

Since magnetic fields do not affect the human senses, you must explore these fields with the help of some device that does respond to them. A simple magnetic compass reacts to a magnetic field by aligning itself parallel to the field. It behaves in this way because the compass is a small permanent magnet pivoted about its midpoint. The **direction of the magnetic field** is defined as the direction in which the N-pole of the pivoted needle points.

The technique of exploring a magnetic field is shown in Fig. 22–1. First, the compass is placed near the N-pole of the permanent magnet and a small dot is placed on the paper near each end of the magnetic needle. Next, the compass is moved so that its S-end is just over the dot that formerly marked its N-end. Now another dot is made to mark the new position of the N-end. This process is repeated until the compass returns to the S-pole of the permanent magnet or leaves the plotting paper. A smoothly curved line can now be drawn through all the dots. Such a line is frequently called a **line of magnetic force.**

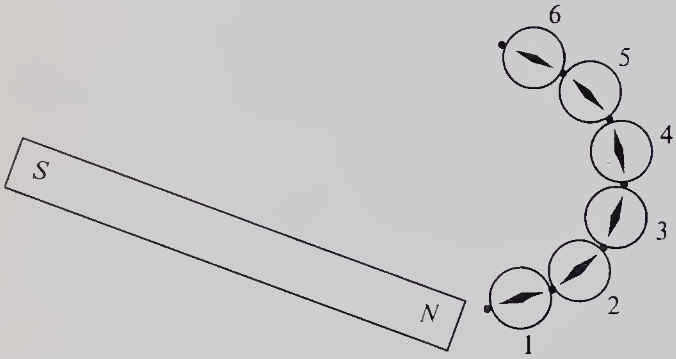


Fig. 22–1 Six successive positions of the exploring compass are shown here. Between each is a dot on the paper, which marks the N-end of one compass position and the S-end of the next.

Equipment

Bar magnets, a pair for each group of students; 1 small compass for each group.

Procedure

STEP 1 Select plotting paper large enough to permit a thorough exploration of the field. Place your magnet near the center of the paper and draw a line around the magnet. Label the poles. Once the magnet and paper are in position, do not move either one until all plotting is completed. Do your plotting in a place that is several feet away from iron and steel objects and from electric circuits. Tap the compass lightly before observing the direction. Indicate the direction of the field by arrowheads on the line you draw.

STEP 2 Plot several lines of force by the method described in Step 1.

STEP 3 Use your compass needle to explore the region between two of the lines you have drawn.

STEP 4 Use your compass needle to find out whether the field is two-dimensional or three-dimensional.

Discussion

1. In general, from what region of the magnet do the lines of force leave? To what region do they return? Are there any lines that seem to leave and never to return? If so, describe them.
2. Do lines of force cross each other?
3. Are there regions between the lines in which there is no field? What is your evidence?
4. Is the field 2-dimensional or 3-dimensional? What is your evidence?
5. Magnetic lines of force are sometimes compared with meridians or parallels of latitude on the surface of the earth. In what ways are all of these lines similar?

6. Are the lines of force you have plotted those of the magnet, those of the earth's magnetic field, those of the compass needle, or a combination of some of these fields? How could you test your answer?
7. Frequently the field of a permanent magnet is not symmetrical. Can you suggest reasons for this?
8. According to the magnetic theory, every magnetic line of force is a closed curve, one that comes back to its starting point. On your paper you have not plotted complete curves. Where is the rest of the curve? In what direction does it go?

For Further Investigation

1. On a fresh sheet of paper place a permanent magnet and a magnetic compass approximately as shown in Fig. 22–2. Pencil an arrow on the paper under the compass to indicate the direction of the field at this point. Carefully rotate the paper, compass, and magnet through 90° and again record the direction of the compass needle. Repeat until the paper and magnet are back as at the start. Discuss your observations.
2. Repeat the steps of the *Procedure*, using two permanent magnets close to each other or one permanent magnet and a nearby piece of unmagnetized iron or steel.

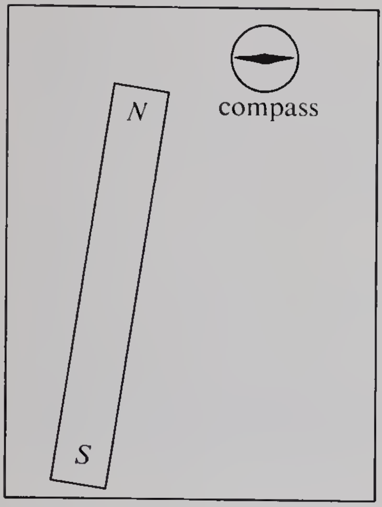


Fig. 22–2 The magnet and compass should be kept in the same relative position while the paper is rotated.

INVESTIGATION

23

The Magnetic Field Surrounding an Electric Current

Introduction

In 1820, while experimenting before a group of his students, the Danish physicist Hans Christian Oersted discovered that a wire carrying a current is surrounded by a magnetic field. Your purpose today is to investigate the direction and shape of the field when current exists in a straight wire and in a coil. You will also observe the effect of the nature of the core on the strength of the field.

In Part A you will investigate the magnetic field around a straight wire and will find a rule for predicting its direction when you know the direction of the current. In Part B you will first use the rule you found in Part A to predict the direction of the field around a coil, and then you will test your prediction.

You will use compass needles to determine the field direction. Remember that the field direction is defined as the direction in which the N-pole of the needle points.

Equipment

Dry cell (preferably not a new one); bell wire; small compasses; switch.

A. THE FIELD AROUND A STRAIGHT WIRE

Procedure

STEP 1 Punch a small hole in the center of a piece of cardboard and thread bell wire through the hole. Support the cardboard between books so that the wire goes vertically through the hole. Connect the ends of the wire to a dry cell and switch, as shown in Fig. 23–1. Place 6 small compass needles on the cardboard at equally spaced intervals around the wire. If you do not have 6 compass needles, use fewer, moving them after you have made your observations.

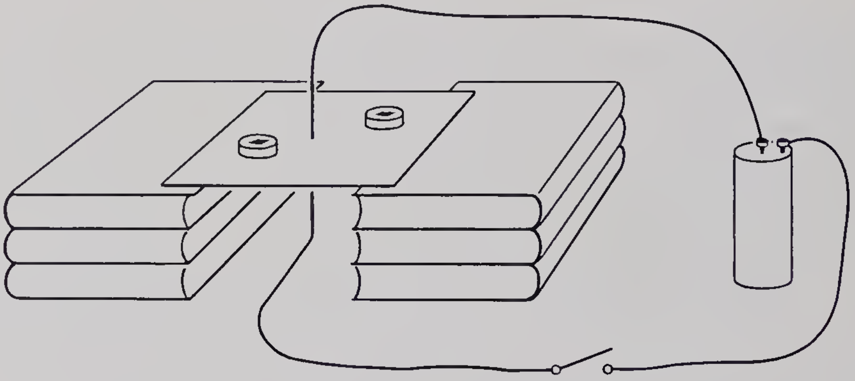


Fig. 23–1 When the switch is closed, the compass needles on the sheet of cardboard will deflect, showing the direction of the field at various points.

STEP 2 Close the switch and observe what happens to the compass needles. **Do not leave the switch closed for more than a few seconds at a time. This experiment is hard on dry cells.**

STEP 3 Make a drawing to show the direction of the field around the current. The center post of your dry cell is positive; the edge post is negative. Electrons move from the negative post, through the wire, and back to the positive post. Show in your drawing the direction of electron flow.

STEP 4 Reverse the direction of the current and repeat the experiment, making a new drawing.

Discussion

1. What is the shape of the field around a straight wire?
2. If you place the thumb of your left hand along the wire, pointing in the direction of the electron flow, what can you do with the other fingers to show the direction of the field?
3. Which is stronger, the earth's magnetic field or that created by the current you used in this investigation? What is your evidence?

B. THE FIELD AROUND A COIL

Procedure

STEP 1 Formulate a hypothesis about the field. To do this, imagine a wire that is bent into a loop like that in Fig. 23–2. Use the left-hand rule (Discussion 2, above) to determine the direction of the field at the points marked with letters. What do you predict about the field inside the loop of wire? What do you predict about the field outside the loop of wire?

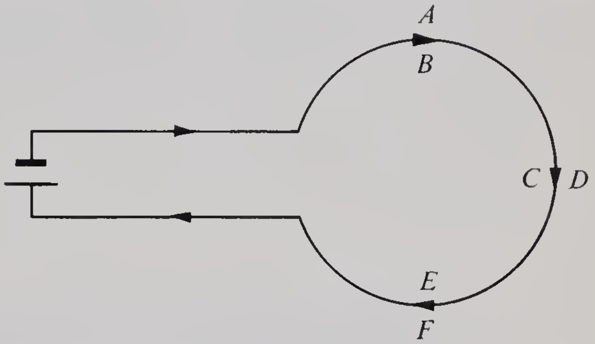


Fig. 23–2 The arrows in this diagram indicate the direction the electrons move in the wire. The symbol at the left represents a dry cell with its negative terminal represented by the shorter line.

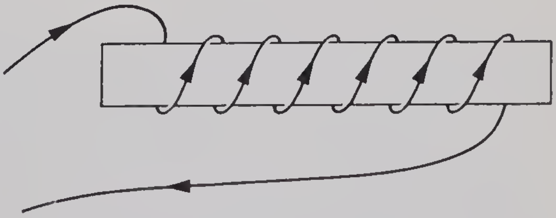
Now imagine that instead of one loop of wire, you have a long coil, as in Fig. 23–3. Use the left-hand rule again to predict the direction of the field around the coil. Make a drawing similar to Fig. 23–3 and draw arrows to show how you think the field will look. This drawing represents the hypothesis that you will test.

STEP 2 Wind bell wire around a pencil to make a coil like that of Fig. 23–3. Devise a method of testing your hypothesis. Describe your method and your results.

STEP 3 Investigate the effect of reversing the current and of changing the direction in which the coil is wound. Make clear drawings to show your results. The coil may be considered to be similar to a bar magnet. In each drawing mark the end of the coil that has an N-pole.

STEP 4 Compare the magnetic field produced by the coil of wire when it has the pencil as a core; when it has an air coil (pencil slipped out); and when it has an iron coil (large nail). Be sure the nail has not been magnetized previously. Describe your methods and the results.

Fig. 23–3 The arrows show the direction the electrons move in this coil.



Discussion

1. Was your hypothesis correct? If not, make a revised drawing to show the shape of the field.
2. If the fingers of your left hand circle the coil in the direction of electron flow, does the thumb point to the N-pole or to the S-pole of the coil?
3. What is the effect of the nature of the core on the strength of the field of the electromagnetic coil?
4. What are some advantages of an electromagnet over a permanent bar magnet?
5. You have studied three kinds of field: electric, magnetic, and gravitational. One of the three is called a weak field and the other two are called strong. Which one do you think is considered to be a weak field? Why?

For Further Investigation

In this investigation you observed the effect of a change in the core on the strength of the field. What other factors probably influence the field? How could you test them to see how they affect the field? Design and perform an experiment to make the test.

INVESTIGATION

24

Introduction to Electric Circuits

Introduction

A law in physics usually expresses a mathematical relationship between certain quantities. Newton's law of gravitation, for example, can be written as the equation

$$F = G\frac{m_1 m_2}{s^2}$$

where m_1 and m_2 are two masses, s the distance between their centers of gravity, F the force between them, and G the gravitational constant. Hooke's law is written as $\Delta l = k\Delta F$, where Δl is the change in length of an object (a spring, a cable, a girder) when it is compressed or stretched by a force change of ΔF, and k is a constant.

These two laws are not equally good. The law of gravitation is so accurate that when it is used to calculate the orbits of most planets, the planets are found to be on time to the second, year after year. Hooke's law, however, is only approximately true, and fails completely if you stretch a wire or compress a beam too much. The law of gravitation appears to be a very good description of the nature of the universe; it is a *theoretical law*. Hooke's law is a rule-of-thumb kind of law, very useful to a man designing a bridge or a skyscraper, but one which he must use with caution, allowing a large safety margin when he draws his plans; it is an *empirical law.*

In this investigation you will explore the relationship between current and potential difference in a circuit. You are to design a circuit that will help you to answer the question: As the potential difference across a resistor in a dc circuit increases, what happens to the current? In addition, try to decide whether the relationship is empirical or theoretical.

Equipment

Dc ammeter; dc voltmeter; source of emf; connecting wire; switch; resistor.

Procedure

STEP 1 If you do not already know the symbols used to indicate parts of an electric circuit, learn them. (See Fig. 24–1.)

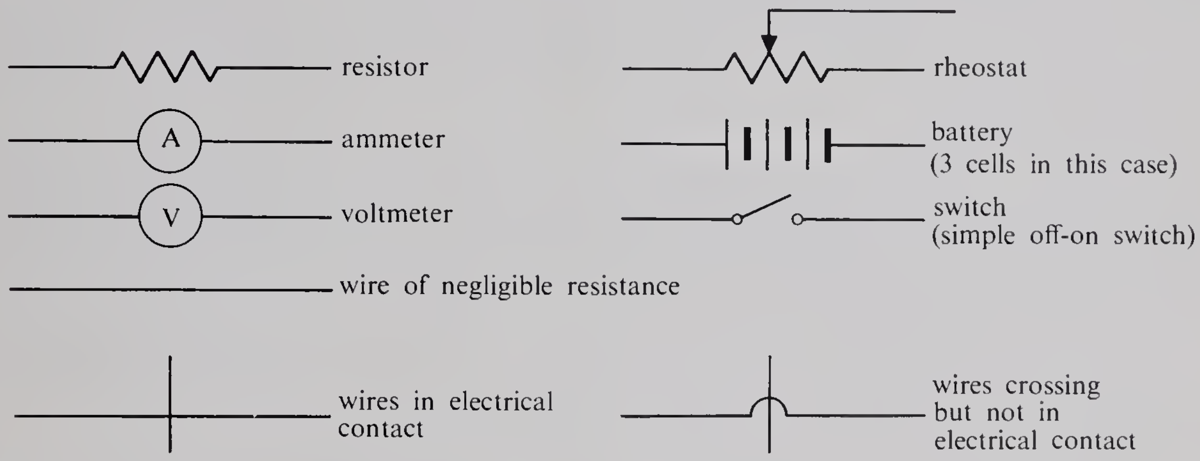

resistor
rheostat
A
ammeter
battery
(3 cells in this case)
V
voltmeter
switch
(simple off-on switch)
wire of negligible resistance
wires in electrical contact
wires crossing but not in electrical contact

Fig. 24–1 Symbols for electric circuits.

STEP 2 Rules for circuit connections:

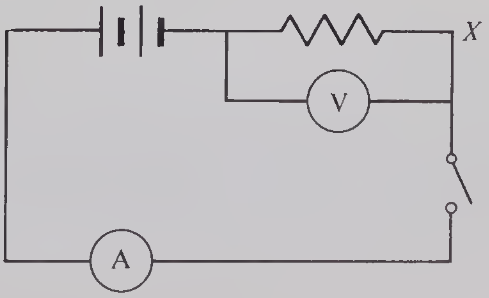
Ammeters are always connected in series. (See Fig. 24–2.)
Voltmeters are always connected in parallel. (See Fig. 24–2.)
Terminal marked + on any meter must be on the + side of the emf.

Emf means electromotive force and refers to the source of potential difference, a battery, a generator, the leads from a power supply, a wall socket, etc.

Never close the switch in your circuit until your wiring has been approved by your teacher.

STEP 3 Make a diagram of the circuit you think you need to answer the question that was stated in the introduction of this investigation. Choose the equipment you need from the supply available. Be sure you have planned a method for changing the potential difference during the experiment. Set up your circuit and have it approved by the teacher.

Fig. 24–2 An ammeter and a voltmeter in a circuit.



STEP 4 Set up a data sheet and record your data.

STEP 5 Decide what to do with the data in order to use them to answer the question. You may include computations or graphs or both.

STEP 6 Do not disconnect your circuit until you have read Discussion Questions 3, 4, and 5 and made the change indicated in Question 5.

Discussion

1. What is the relationship between potential difference and current for your resistor?
2. Do there seem to be any limitations to the relationship you have just stated? Is the relationship highly precise, probably having a theoretical basis, or is it an empirical one, true within limits? Give reasons for your answer.
3. If the meters in your circuit were arranged as in Fig. 24–2, what assumption did you make about the current in the resistor? In the voltmeter?
4. If you arranged your meters with the ammeter at the corner marked *X* in Fig. 24–2, what assumption would you be making about the potential difference across the resistor? Across the ammeter?
5. Ammeters and voltmeters are designed in such a way that it is hoped that all of these assumptions are justified. Try moving your ammeter from one of the positions described above to the other. How much do the ammeter and voltmeter readings change? Does this introduce an appreciable error in your experiment?
6. The relationship between current and potential difference is known as **Ohm's law.** It is used to define the unit of electric resistance, the **ohm.** Using *I* for current, *V* for potential difference, and *R* for resistance, write Ohm's law and define the ohm.
7. Calculate the resistance of the resistor you used in this experiment.

For Further Investigation

Investigate the limitations you suggested in your answer to Discussion Question 2.

INVESTIGATION

25

Potential Difference and Current in a Network

Introduction

In the simple circuit of Fig. 25–1 a stream of electrons moves around in a clockwise direction. It is often useful to think of the path they follow as similar to a mountain trail. As the electrons leave the negative terminal of the battery, *A*, they are at the top of the mountain. Like a rock on a mountain top, they have potential energy. As they go downhill through R_1, they lose energy, which is converted to heat. They lose more energy going downhill through R_2. When they get back to *B*, they are at the bottom of the mountain. From *B* to *A*, in the battery, they climb once again to the top.

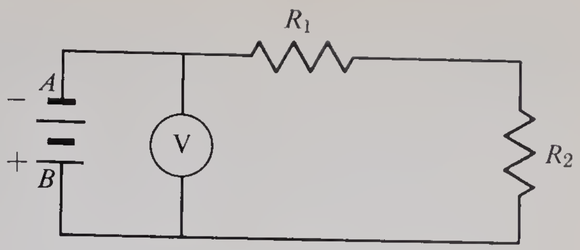


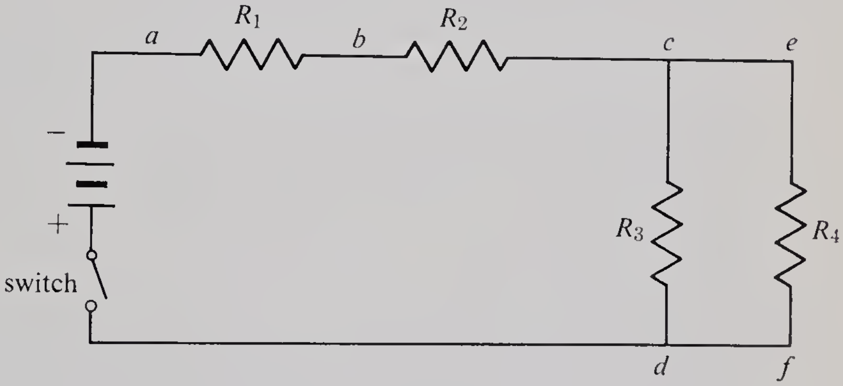
Fig. 25–1 A simple dc circuit.

The voltmeter in the circuit measures the potential difference across the battery; this corresponds to the height of the mountain. An uphill potential difference like that in the battery is called an **emf.** The voltmeter also measures the potential difference across the rest of the circuit, the downhill distance through R_1 and R_2. This downhill potential difference is called the **potential drop.** Since you can use Ohm's law ($V = IR$) to calculate the potential drop, it is also called the **IR drop.**

In this investigation you will measure the potential difference and current at various places in a circuit containing both series and parallel resistors in order to understand more clearly the rules governing the behavior of an electric circuit.

The circuit you will use is diagramed in Fig. 25–2. The values of R_2 and R_3 are equal; the other resistors have different values. Some of the questions you will be answering are these: Is the current in a circuit the same in all places? How do the *IR* drops in a circuit compare with the emf of the circuit?

Fig. 25–2 In this circuit $R_2 = R_3$.



Equipment

Dry cells or other dc-power supply; 4 resistors of known resistance (2 of them to be equal in resistance); knife switch; connecting wire; ammeter and voltmeter.

Procedure

STEP 1 Set up the circuit of Fig. 25–2. Copy the diagram on your data sheet and record on the diagram the resistance of each resistor.

STEP 2 Use a voltmeter with test prods so that the potential difference between any two desired points can be measured. A good practice is to use a red lead on the positive terminal and a black one on the negative terminal. The negative terminal of the meter is the end into which electrons flow. Electrons enter the meter from the negative terminal and leave it through the positive. You should be able to figure out in each case where to put the two voltmeter prods. If you make a mistake, the needle of the meter will move in the wrong direction and the meter may be damaged. On the diagram on your data sheet, mark the negative end of each resistor with a − sign and the positive end with a + sign.

STEP 3 Close the switch of your circuit. On a data sheet record the potential difference across the battery, R_1, R_2, R_3, R_4, and across R_1 and R_2 together.

STEP 4 In order to measure current, you will have to break the circuit at various places to insert the ammeter. As with the voltmeter, electrons enter the ammeter through the negative terminal. Measure and record the current at *a*, at *b*, between R_2 and *c*, between *c* and *d*, between *e* and *f*, between *d* and the switch.

Discussion

In order to draw conclusions, you will compare the results on your data sheet. Keep in mind that there is experimental error in the data. When you are asked whether or not two measurements are equal, you should ask yourself whether the differences between them are small enough to be due to experimental error. If they are, then the two measurements may be considered to be equal.

1. When two resistors are in series, are the currents equal? If not, which resistor has the larger current? Does this seem reasonable? Why?
2. When two resistors are in parallel, are the currents equal? If not, which resistor has the larger current? Does this seem reasonable? Why?
3. A point where several wires join in a circuit (points *c* and *d*, for example) is called a junction. If you call the current entering a junction positive and a current leaving a junction negative, what is the sum of the three currents at point *c*? At point *d*? In general what seems to be the sum of the currents at a junction? The statement about the sum of the currents at a junction is known as **Kirchhoff's first rule.** Does it seem reasonable? Why?
4. If two resistors are in series, are the potential drops equal? If not, which resistor has the larger potential drop? Does this observation support Ohm's law? Give reasons for your answer.
5. If two resistors are in parallel, are the potential drops equal? If not, which resistor has the larger potential drop? Does this observation seem reasonable? Why?
6. Imagine that you are walking around the circuit of Fig. 25–2 in a clockwise direction from the battery, through R_1, R_2, R_3, and back to the battery. Whenever you go through a potential difference from + to −, call it a positive potential difference. Whenever you go through from − to +, call it a negative potential difference. What is the sum of the potential differences around this closed loop? What is the sum of the potential differences around the loop that includes the battery, R_1, R_2, and R_4? In general, what seems to be true of the sum of the potential differences around a closed loop? This statement is known as **Kirchhoff's second rule.** Does it seem reasonable? Give your explanation in terms of the mountain analogy of the introduction.
7. Are Kirchhoff's rules empirical (like Ohm's law) or have they a theoretical base? Give reasons for your answer.
8. The path *c-e-f-d* in Fig. 25–2 is a closed loop. How can Kirchhoff's second rule be applied to it?

INVESTIGATION

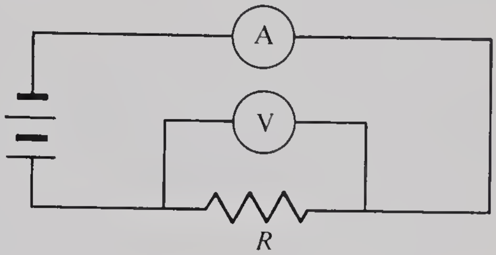
26

The Accurate Measurement of Resistance

Introduction

The circuit of Fig. 26–1 can be used to measure resistance, as you learned in Investigation 24. However, the accuracy of this procedure is limited by the fact that the voltmeter conducts some electrons, and therefore the ammeter measures not merely the current in the resistor, but also the current in the voltmeter. In the present experiment you will use the resistance-measuring circuit known as the **Wheatstone bridge,** which provides remarkably accurate results.

Fig. 26–1 The volt-ammeter method for measuring resistance.



Equipment

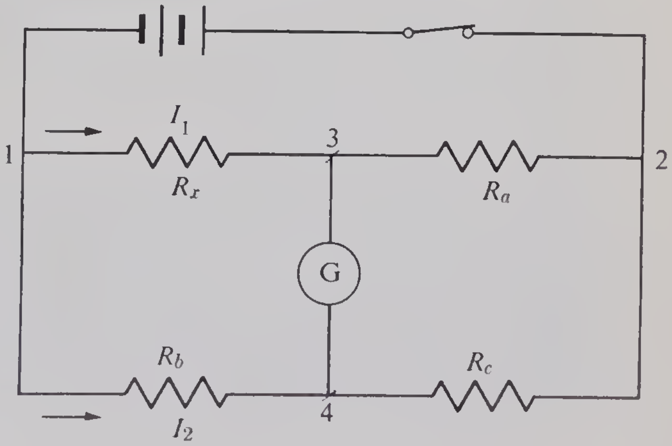
Slide-wire bridge; galvanometer with protective resistor; 1 or 2 dry cells; dial resistance box or other form of variable standard resistance coils; 2 or more premeasured "unknown" resistors; switch; and lead wires.

Procedure

The Wheatstone-bridge circuit is shown in Fig. 26–2. R_x is the unknown resistor, while the others are known and at least one of them is adjustable to a variety of known values. The galvanometer, G, is a sensitive ammeter with zero in the center of the scale. When you use the circuit, you adjust the variable resistors until the galvanometer reading is zero.

Before you start your investigation, in order to understand how the Wheatstone bridge measures resistance, write out the answers to the following questions. When you come to the end, you will have an equation that can be used to calculate the resistance. All of the questions refer to Fig. 26–2.

Fig. 26–2 The basic circuit for a Wheatstone bridge.



a) The current in R_x is I_1. If there is no current in G, what is the current in R_a?
b) The current in R_b is I_2. If there is no current in G, what is the current in R_c?
c) What is the IR drop between Points 1 and 3?
d) What is the IR drop between Points 1 and 4?
e) If there is no current in G, how are these IR drops related? Write your answer as an equation.
f) In a similar way, compare the IR drops between Points 3 and 2 and between Points 4 and 2. Write the equation.
g) Divide the equation you wrote in (e) by the one you wrote in (f) above. If you have done the other steps correctly, the result is an equation in which the I's cancel out.
h) Solve the equation for R_x. All other quantities in the equation are known.
i) Figure 26–3 is a diagram of a typical student Wheatstone bridge. As before, R_a has a variable resistance of known value and R_x is the unknown. However, a single length of resistance wire is substituted for R_b and R_c. A sliding contact at Point 4 makes R_b and R_c variable, although their sum remains a constant. The resistances of R_b and R_c are proportional to their lengths, L_b and L_c. Express the ratio R_b/R_c in terms of L_b and L_c.
j) Substitute this new ratio in the equation for R_x and record the result.

The chief limitations to the accuracy of this procedure are the precision with which the values of R_a, R_b, and R_c are known, and your carefulness in adjusting the circuit to make the galvanometer show zero current.

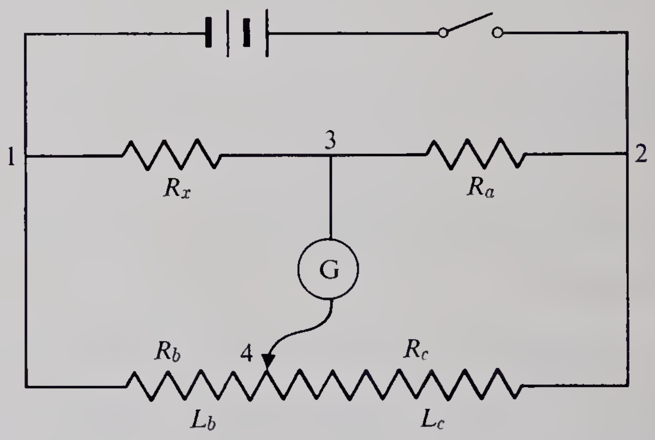


Fig. 26–3 In the slide-wire form of the Wheatstone bridge, a length of resistance wire is substituted for resistors R_b and R_c.

STEP 1 Examine your slide-wire bridge and identify L_b, L_c, the places where you must connect the galvanometer, R_x, and R_a. Wire the circuit. Be sure all points at which connections are made are clean and bright, that the connecting wires are also clean and bright, and that connections are tight.

STEP 2 Clean the slide wire but do not use any abrasive such as sandpaper on it.

STEP 3 As you use the bridge, keep the sliding contact somewhere near the midpoint of the wire and make initial adjustments with the dial resistance box. When the galvanometer needle is close to zero, move the sliding contact to bring the needle to zero.

STEP 4 The galvanometer has a high protective resistance built into it. When you have almost reached a balance, press down the galvanometer button to short out the protective resistance and then complete the balance.

STEP 5 Set up a data sheet that shows clearly your measured data and the computed results. Measure the resistance of two or more unknowns, as directed by your teacher. Submit the results to the teacher for checking.

Discussion

1. Steps 1, 2, 3, and 4 contain specific instructions about how to prepare and use your bridge. In each case tell why the methods described were desirable.
2. What seem to you to have been the greatest possible sources of error in your measurements of resistance?
3. The Wheatstone bridge is not very accurate in measuring extremely small resistances. Why?
4. A telephone line is out of order because of a short circuit. The cable is underground and the repairmen would like to know the approximate location of the short circuit before starting to dig. At headquarters they use a Wheatstone bridge to measure the resistance of the line that is shorted. How does this information help them? What else do they need to know in order to locate the short?

For Further Investigation

1. Examine an enclosed-dial type of Wheatstone bridge and describe its construction. Use it to check the resistances you have just measured.
2. Use the Wheatstone bridge to measure the resistance of two of your unknown resistors in series and in parallel. How do the results compare with the values obtained by computation, using the laws for series and parallel resistors?

INVESTIGATION

27

The Operation of a Simple Electric Motor

Introduction

In the ordinary household more electric power is used for lighting than for any other purpose. However, because of the tremendous use of electricity in modern industry and transportation, the nation as a whole uses more electric energy to operate electric motors than for any other purpose. In this experiment you will study a simple student motor, especially designed to help you become familiar with the principles on which electric motors operate.

As you follow the steps under *Procedure*, answering all the questions, you should find that your understanding of the operation of an electric motor increases. Instead of asking for a written report, your teacher will give you a set of questions to test your understanding when you have finished.

Equipment

St. Louis motor; dc source; wires; knife switch; magnetic compass.

Procedure

STEP 1 Your motor is arranged so that it can be used either with a pair of permanent magnets or with an electromagnet for the field. For this part of the investigation, however, you should use no field at all. The armature of the motor (often called the rotor) is a simple electromagnet pivoted around its midpoint. It receives current through the two brushes and the two commutator sections. Connect the brushes in a circuit with a battery and a switch, as shown in Fig. 27–1. Be sure that the brushes, whose position may be adjustable, are in the position shown in the diagram.

STEP 2 Before closing the switch, examine the armature circuit closely. Start at the negative terminal of the battery and follow the circuit through the first brush, the commutator section which it touches, around the coil, out through the other commutator section and brush, and back to the battery. Decide which end of the armature (upper or lower in Fig. 27–1) will be the N-pole. Then close the switch and check your prediction with a magnetic compass. Does your observation agree with your prediction?

STEP 3 Now examine the contacts between the brushes and the commutator sections while you slowly rotate the armature. Do the same brushes always touch the same commutator sections? What happens to the direction of electron flow through the armature winding when the brushes "swap" commutator sections? As a result, what happens to the magnetic polarity of the armature? With reference to Fig. 27–1, in what position is the armature when this change occurs (up and down, left to right, or diagonal)? Now check the armature with your magnetic compass. Do your experimental observations agree with your theoretical predictions?

Fig. 27–1 For a preliminary study, the armature only is used.

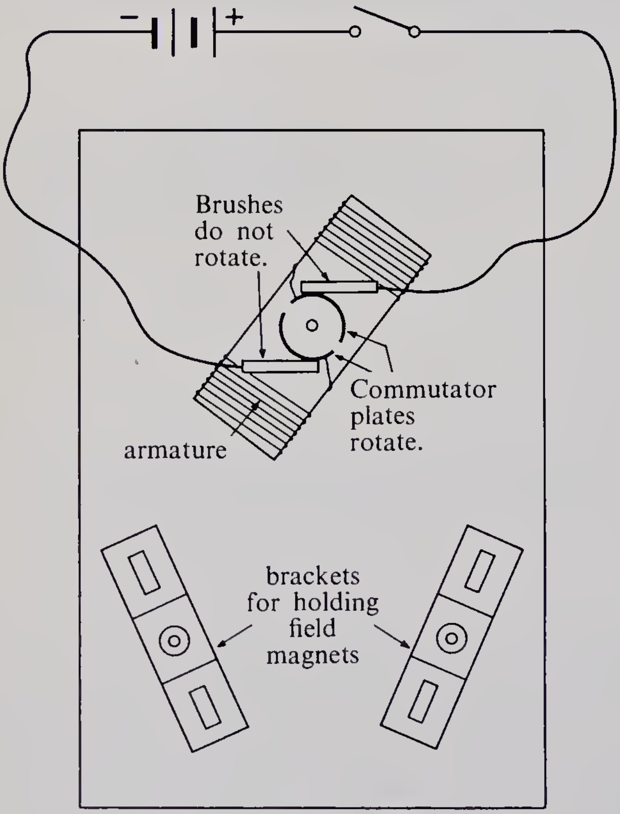
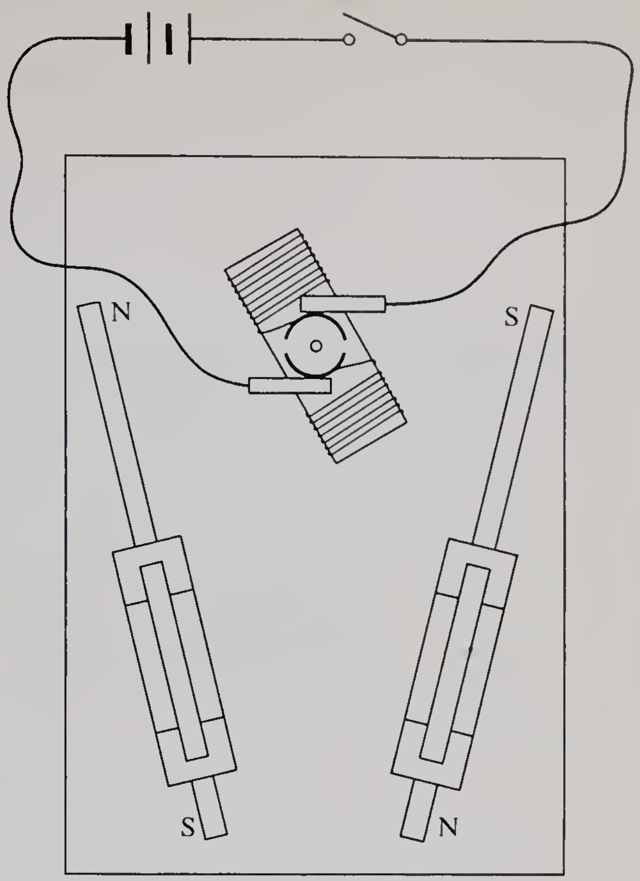


Fig. 27–2 Two bar magnets can be arranged to form a permanent field for the student motor.



STEP 4 If the polarity of the armature changes every half revolution, there should be one region where an armature pole is always N and another region where an armature pole is always S. These regions are semicircles. In Fig. 27–1 what is the location of the semicircle in which the armature pole is always N (upper half, lower half, right-hand half, left-hand half)?

STEP 5 Now insert the permanent magnets into their holders to form a field for the motor (Fig. 27–2). Adjust their position so that the tips of the armature just miss them. Should the armature of Fig. 27–2 turn in a clockwise direction, counter-clockwise direction, or stand still when you close the switch? What will happen when the armature gets to the position shown in Fig. 27–3? Close the switch to check your predictions.

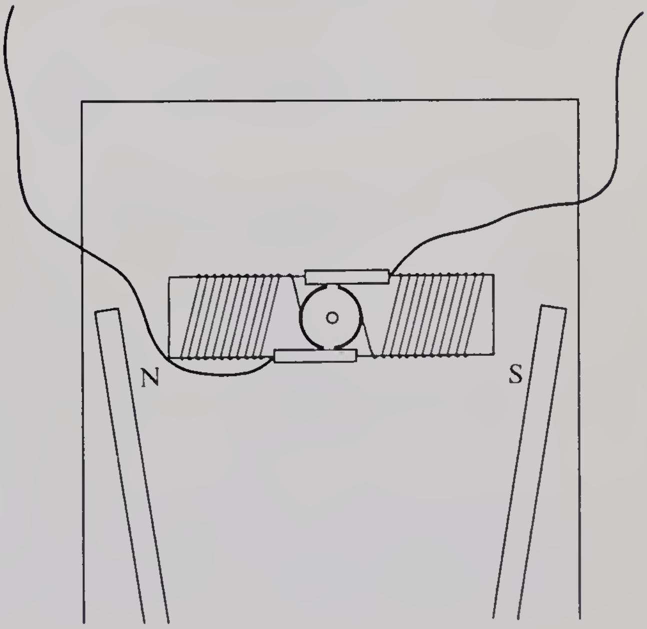


Fig. 27–3 What happens when the armature is in this position?

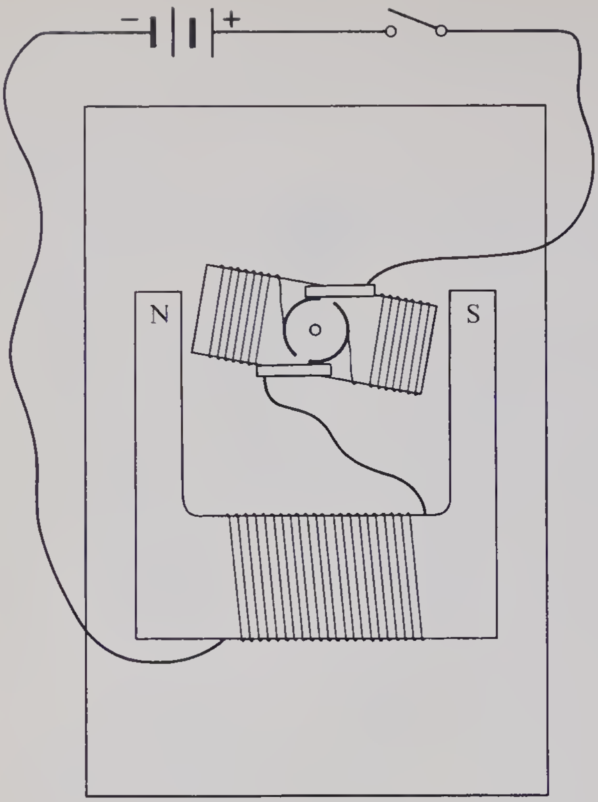


Fig. 27–4 The student motor can be equipped with a field formed by an electromagnet.

STEP 6 Replace the permanent magnets with an electromagnet, as shown in Fig. 27–4, and connect the armature and electromagnet in series. Arrange the circuit so that the polarity of the field magnet is as shown and check it with a magnetic compass to make sure it is correct. In which direction does the armature rotate? Is this the same direction as when you used the permanent magnets?

STEP 7 Can you find an armature position from which the motor will not start without some help from you? With which of the diagrams in this investigation does this position correspond? Since this position exists twice during each revolution, how is the motor able to have continuous motion once it is started?

Discussion

Obtain from your teacher a set of questions based on Fig. 27–5 and answer them.

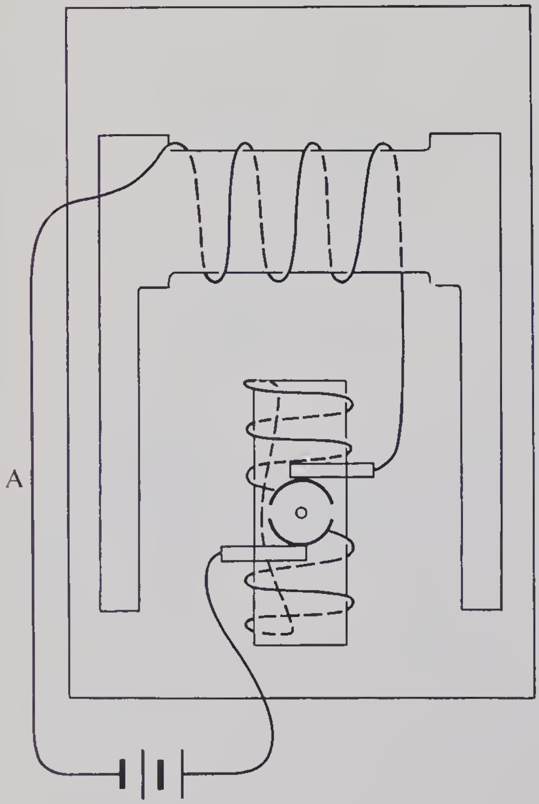


Fig. 27–5 Motor diagram to accompany the Discussion.

INVESTIGATION

28

Electromagnetic Induction

Introduction

Imagine that you can examine a copper wire greatly magnified. You find it composed of many copper atoms, each with a positive nucleus surrounded by electrons. The nucleus attracts the electrons with a force that keeps most of them in place, but a few of the outer electrons are less tightly bound. For this reason they can sometimes be induced to move. If, for example, you attach the ends of the wire to the terminals of a dry cell, electrons near the negative end of the cell are repelled from it and those near the positive end of the cell are attracted. Thus many electrons start to move, all in the same direction, and a current exists in the wire.

Exactly how a dry cell gets to be positive at one terminal and negative at the other is a matter involving some rather complicated chemistry. In this investigation, you will observe another way in which electrons can be induced to move in a conductor, and you will draw some conclusions about the laws governing electromagnetic induction.

The investigation is in two parts. In the first part you will investigate the ability of a permanent magnet to cause electrons to move in a coil of wire. In the second part you will investigate the ability of a current in one conductor to induce a current in another conductor insulated from the first one. As you do the experiment, be looking for general rules that seem to describe what is going on. At the end you should be able to state two rules, or laws, both of which apply to both parts of the investigation.

Equipment

Galvanometer; protective resistors (4000 to 50,000 Ω) if galvanometer is not protected; bell wire; dry cell; large nail (4 to 6 in.); magnet (bar or cylinder); switch.

A. INDUCTION BY A PERMANENT MAGNET

Procedure

STEP 1 A galvanometer detects small currents and shows their direction. Your first problem is to investigate the relationship between the direction in which the galvanometer needle deflects and the direction in which electrons are moving through the instrument. Since a galvanometer is easily damaged by too large a current, it must be protected for this part of the experiment. Your teacher will tell you whether your galvanometer has a built-in protective resistor and how to use that protection. If it does not, put a protective resistor in series with the galvanometer and connect the circuit, as shown in Fig. 28–1. Record in your *Data Book* the number of your galvanometer.

When you close the switch, in which direction do electrons move through your galvanometer when you are facing the dial? When you close the switch, in which direction does the needle deflect? When the galvanometer needle deflects to the right, in which direction are electrons moving through the galvanometer?

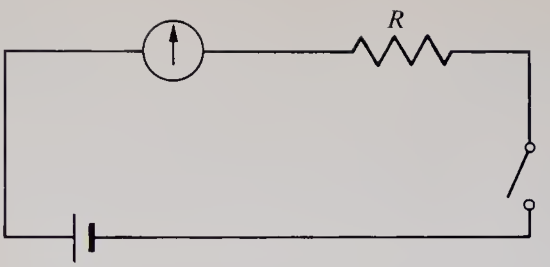


Fig. 28–1 Circuit to test direction of current in the galvanometer. *R* may be omitted if the galvanometer has a built-in protective resistance. Otherwise, *R* should be between 5000 and 50,000 Ω.

STEP 2 Remove the protective resistor from the galvanometer. Make a loose coil (4 to 8 turns) of bell wire and attach the ends (which should be long) to the galvanometer, as shown in Fig. 28–2. Be sure to have the direction in which the coil is wound the same as in the diagram. Insert the north pole of a magnet into the end of the coil as shown. Do not let the coil move.

What happens to the galvanometer needle when: **a)** The north pole is entering the coil? **b)** The north pole is at rest in the coil? **c)** The north pole is pulled out of the coil? **d)** The north pole is at rest outside the coil?

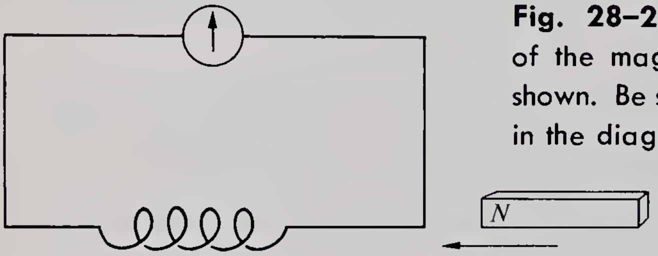


Fig. 28–2 The coil is held stationary, and the N-pole of the magnet approaches the coil in the direction shown. Be sure the coil is wound in the direction shown in the diagram.

STEP 3 Now hold the magnet steady and move the coil toward it, as shown in Fig. 28–3. What happens when: **a)** The coil approaches the north pole of the magnet? **b)** The coil is stationary with the north pole inside it? **c)** The coil moves away from the north pole? **d)** The coil remains stationary outside the magnet?

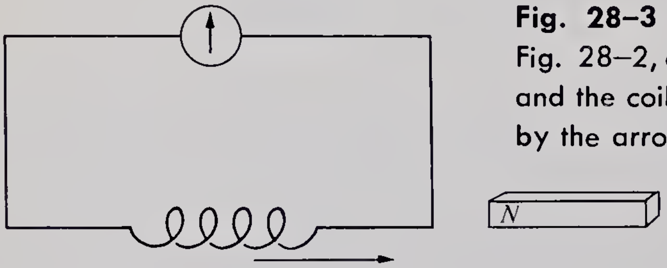


Fig. 28–3 This circuit is identical with the circuit of Fig. 28–2, except that the N-pole is held stationary, and the coil is moved toward it in the direction shown by the arrow.

STEP 4 Using the information you obtained in Step 1, determine the direction of electron movement in the coil when the magnet is moving as shown in Fig. 28–2. Copy the drawing and add arrows to show the direction of the current. Do the same for Fig. 28–3.

STEP 5 As you learned earlier, a current in a coil makes an electromagnet of the coil. Use the hand rule that applies to such a coil to determine the north pole of the coil of Fig. 28–2; then mark it with an N in your drawing. Do the same for Fig. 28–3.

Discussion

1. From your data, as shown in the drawings, answer these questions:
   - **a)** If the north pole of a magnet approaches a coil of wire, what kind of magnetic pole is induced in the end of the coil closest to the magnet?
   - **b)** Do these two poles attract or repel each other?
   - **c)** Does the force between the poles help the motion or hinder it?
   - **d)** If the north pole of a magnet moves away from a coil of wire, what kind of magnetic pole is induced in the end of the coil closest to the magnet?
   - **e)** What is your evidence for the statement made in **(d)**?
   - **f)** Do the two poles described in **(d)** attract or repel each other?
   - **g)** Does the force between the poles help or hinder the motion?
2. Under what conditions will a magnet induce a current in a coil?
3. What is always true about the direction of the induced current?

B. INDUCTION BY A CHANGING CURRENT

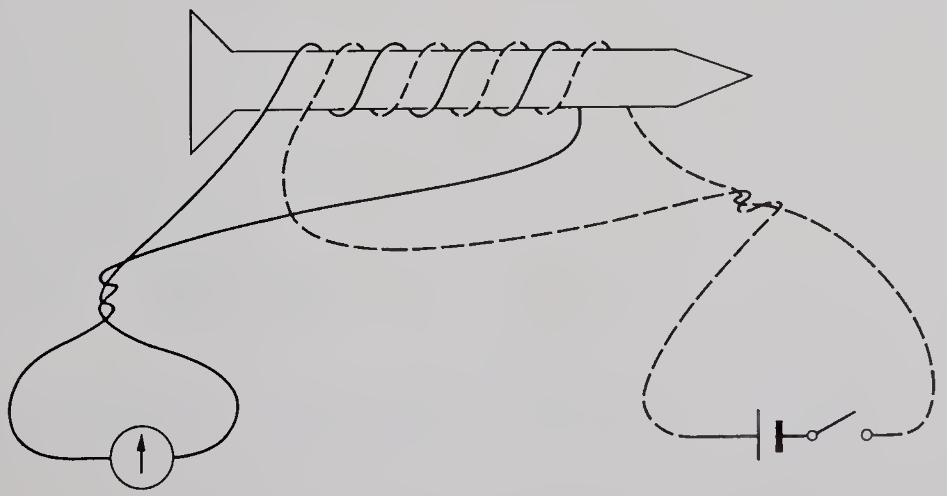
Procedure

STEP 1 Wind 40 turns of bell wire tightly around a large nail (4 to 6 inches long) and twist the ends together near the head of the nail. The twisting is done to hold the wire on the nail, not to make a connection. Be sure the twisted part of the wire has insulation on it. Wind 40 turns of another piece of wire in the same direction on top of the first coil. Twist the ends together and make the connections shown in Fig. 28–4. The coil connected to the dry cell is called the **primary;** the other is the **secondary.**

What happens to the galvanometer needle in the secondary circuit when the switch in the primary circuit is: **a)** First closed? **b)** Kept closed? **d)** First opened? **d)** Left open?

Is current induced in the secondary when current in the primary is increasing, decreasing, steady, or 0? (List all possibilities.)

Fig. 28–4 Two coils, insulated from each other, are wound on the same core.



STEP 2 From the way in which you have connected your dry cell, you know the current direction in the primary. Does this current make the head of the nail a north or a south magnetic pole? (Use your hand rule.)

From the deflection of the galvanometer needle, you know the direction of current in the secondary. When the switch is first closed and current is increasing in the primary, does the current in the secondary tend to make the head of the nail a north or a south magnetic pole?

Does the magnetic field created by current in the secondary help or hinder the growth of the magnetic field created by the primary?

STEP 3 When the switch is opened, and current is diminishing in the primary, does the current in the secondary tend to make the head of the nail a north or a south magnetic pole?

When the switch is opened, does the magnetic field created by the current in the secondary help or hinder the decrease of the magnetic field of the primary?

Discussion

1. Under what conditions will a current in a wire induce a current in another wire that is insulated from the first one?
2. What is always true about the direction of the induced current?
3. What was the situation that caused current to be induced in both parts of the experiment? Give a single general cause.
4. What is always true about the direction of the induced current? This statement is known as Lenz's law.
5. Show that the answer to Discussion Question 2 follows from the law of conservation of energy.
6. What would have happened in Part A if you had used the south pole of the magnet instead of the north? Try it out if you have time.
7. What would have happened in Part A if you had pushed the magnet in one end of the coil and out the other? Try it if you have time.
8. What would have happened in Part B if instead of connecting the primary to a switch and dry cell, you had connected it to an alternating current source? With alternating current, the electrons in the wire travel first in one direction and then in the other, without getting away from their original position very far. **Do not try this.** It would ruin the galvanometer.

INVESTIGATION

A Simple Alternating-Current Circuit

29

Introduction

If you place a coil of wire in a dc circuit, the resistance of the coil limits the flow of electrons. If you put the coil in an ac circuit, the current is limited not only by the resistance, but also by the back emf induced in the coil. The ability of the coil to produce the back emf is called its **inductance.** The opposition of the coil to the current is called the **inductive reactance** and, like resistance, is measured in ohms.

In the investigation you will observe the behavior of a simple ac circuit containing both resistance and inductance.

In a simple series circuit, containing an ac source, a resistor, and an inductor (coil), you should observe the current and potential difference in various parts of the circuit. You have learned that Kirchhoff's two rules apply to a dc circuit. Do they also apply to an ac circuit? By observing current and potential difference, can you determine the inductive reactance of your coil and can you calculate the inductance?

Equipment

Ac ammeter and voltmeter; ohmmeter or dc ammeter and voltmeter; resistor; inductor; switch; lead wire; ruler; protractor.

Procedure

Before you start your investigation, be sure you know certain facts about *Kirchhoff's rules*, *inductance*, and *inductive reactance*. Answer the following questions and have the answers checked.

a) If Kirchhoff's rules apply to ac circuits, how should I_R, I_L, and I_T in Fig. 40–1 be related?

b) If Kirchhoff's rules apply to ac circuits, how should V_R, V_L, and V_T in Fig. 29–1 be related?

c) In what units is the inductance (L) of a coil measured?

d) In what units is the inductive reactance (X_L) measured?

e) What equation relates inductive reactance to the inductance?

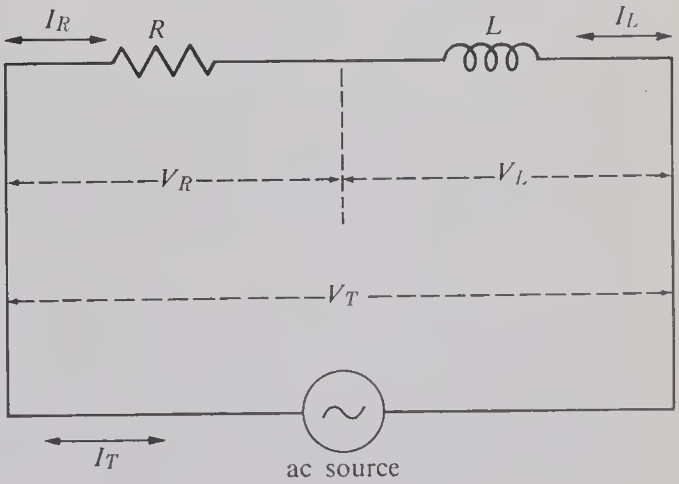


Fig. 29–1 A simple ac circuit containing resistance and inductance.

f) If the current through R is I_R, then $V_R = ?$

g) The coil has resistance as well as inductance. The combined effect of these two is called the **impedance** (Z_L) of the coil. If the current through L is I_L, then $V_L = ?$

h) The opposition of the circuit as a whole to the current is called its impedance (Z_T). If the total current is I_T, then $V_T = ?$

STEP 1 Wire a circuit as in Fig. 29–1. For your ac source use commercial current. Include a switch in the circuit. Since you can get a shock from this current, do not touch any uninsulated wires when the current is on. Use a voltmeter with test prods to check V_R and V_L. If one of them is more than twice as big as the other, substitute another resistor or another coil.

STEP 2 Measure and record on a data sheet the values of V and I indicated in Fig. 29–1. Also record the value of frequency for your ac (probably 60 cycles/sec).

STEP 3 Use your data to calculate R, Z_L, and Z_T, showing the method and results clearly on your data sheet.

STEP 4 Measure the resistance of R and of the coil in a dc circuit. On the data sheet show clearly the method and results.

Discussion

1. Does Kirchhoff's rule about current apply to this circuit? What is the evidence for your answer?
2. Does Kirchhoff's rule about potential difference apply to this circuit? What is the evidence for your answer?
3. You have studied situations in physics where the sum of several quantities is not obtained by simple addition. If you use other methods for adding your potential differences, can Kirchhoff's rule be applied to an ac circuit? Explain, making a careful scale drawing using your data. In the drawing let V_R be represented by a horizontal line. Label the parts of the drawing.
4. Does R as calculated from the ac circuit equal R as calculated from the dc circuit? If there is a difference, account for it.
5. In a resistor in an ac circuit, the current and potential difference are in phase with each other. Therefore in your drawing, you may consider the direction of V_R to be the same as the direction of current. Extend the V_R line and label the extension "current direction." You have probably read that the potential difference in an inductor is out of phase with that of the current by 90°. Do you find that the angle between current direction and V_L in your drawing is 90°? If not, can you think of an explanation for the difference?
6. Find components of V_L in the direction of the current and at a 90° angle to it. Use these components to calculate R_L, X_L, and L. Does R_L agree with the value measured in the dc circuit? If not account for the difference.
7. The phase angle, θ (theta), for the circuit as a whole is the angle between current direction and V_T. Measure it in your drawing.

8. Show with a diagram that the total impedance of an ac circuit containing R and L in series can be calculated from this equation:

$$Z = \sqrt{R^2 + X_L^2}$$

where R is the total resistance of the circuit.

9. Using this same diagram, determine a formula from which you could calculate the phase angle for the circuit as a whole.

For Further Investigation

Repeat the experiment with a capacitor instead of an inductor in the circuit. This may create more difficulties in finding appropriate sizes of capacitors and resistors so that the potential difference across one is not more than twice that across the other. Many capacitors used in radios are designed for much higher frequencies than commercial ac and may not be large enough for your circuit. Capacitors that are large enough are usually electrolytic and are supposed to be used only with dc. They can be used with ac, but they heat up in a very short time and when hot may explode, scattering a jellylike substance around, which is messy. To avoid this, if you use such a capacitor, you must close the switch only for a second or two while taking a meter reading. You must also be careful not to touch a capacitor after you have used it in your circuit unless you have first discharged it, as it may give you an unpleasant shock. If after all of these warnings, you are still interested, go to it!

INVESTIGATION

30

Transformers

Introduction

You often see transformers as large, bushel-sized devices on power line poles, or as even larger units on the ground at electric-power distribution stations. In the house small transformers are often used to operate electric toys or doorbells. But although electric transformers are very common and essential, you may not know just what they do or how they operate. In this experiment you will carry out controlled observations of transformers in action. As a result, you will have a better idea of how they work and also of why they are important in power distribution.

A transformer usually consists of two coils of wire wound on the same iron core but insulated from each other. One coil is connected to a source of emf and is called the primary. The other is connected to a load and is called the secondary. In Part B of Investigation 28 you made a transformer and observed what happens when a direct-current emf is used in the primary. In this investigation you will use an alternating-current source in the primary and will observe what happens in the secondary. You will see how the result is related to the number of turns in the primary and secondary coils.

Equipment

Transformer (commercial or homemade as in Step 1); ac voltmeter.

Procedure

Before you start your investigation, answer these questions (reviewing Investigation 39 if necessary):

a) Under what conditions will a current in the primary induce a current in the secondary of a transformer?

b) If you used ac in the primary, how much of the time would you expect current to be induced in the secondary?

STEP 1 You should have a transformer for which you know the number of turns in the primary (N_1) and in the secondary (N_2). If necessary, you can make it yourself by wrapping two sets of turns of wire around a soft iron core, as in Fig. 28–4, but wind the turns very close together. One winding should have not less than 30 turns, and the other between two and three times that many. Each group of laboratory partners should have a transformer with a different set of values for N_1 and N_2.

STEP 2 Use the circuit of Fig. 30–1 to compare the potential difference across the primary with that across the secondary when there are more turns in the primary than in the secondary and when you have reversed the transformer. Set up a data sheet to show your observations clearly, including the values of N_1 and N_2 each time.

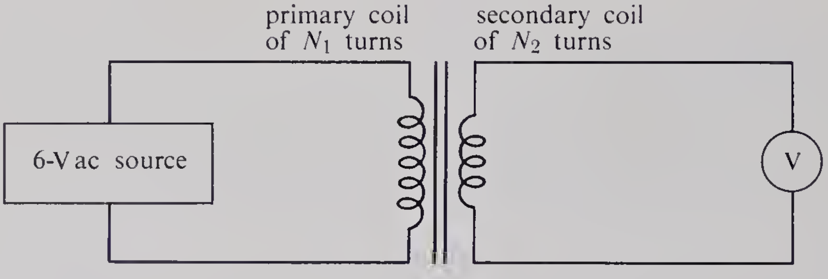


Fig. 30–1 Although both coils are wound on the same core, the symbol for a transformer shows them separated. The lines in the center tell that the core is iron. After you have measured the emf of the secondary, you can use the same voltmeter to measure the potential difference across the primary.

Discussion

1. When there is ac in the primary, how much of the time is there an induced emf in the secondary?
2. When is the potential difference in the secondary greater than that in the primary?
3. When is the potential difference in the secondary less than that in the primary?

4. Let V_1 be the potential difference of the primary and V_2 be the potential difference of the secondary. Compare the ratio of the N's (turns ratio) with the ratio of the V's and write an equation that shows the probable relationship of these four quantities as indicated by your experiment. Take into account the fact that there is unavoidable error in any measurement.
5. In your conclusions you created an equation on the basis of two sets of data only. This is hardly enough information for you to be sure the equation is a good one. Collect data from other students who had different turns ratios. Do their data agree with your equation when you take experimental error into account? Give the data in your answer to this question.
6. Why is an electric transformer usually used with ac?
7. When electric power is transmitted long distances, some of the power is lost as heat in the lines. The power lost in this way is I^2R, where I is the current in the line and R is the resistance of the transmission lines. Obviously the power loss will be small if I is small. How does the use of transformers make it possible to keep I small and yet transmit a great deal of power over long lines?

For Further Investigation

1. Test the efficiency of a small step-down transformer operated from a 120-volt line, one such as an electric train or a door-bell transformer. To do this, load the secondary with a normal load and measure the power (with an ac wattmeter) in the primary and secondary circuits. Well-designed transformers of large size often have efficiencies in excess of 99%. How does your small one compare with this standard?
2. Use a commercially constructed transformer (such as the one used in Item **1** above) to measure the power consumed in the primary circuit when the secondary circuit is open and when it is used to ring a doorbell or run a train. From this observation, can you tell whether or not it is poor economy to have a bell-ringing transformer for a doorbell hooked across a 120-volt ac house electric system 24 hours a day, every day of the year? Account for the difference in power consumption in the two cases.

INVESTIGATION

31

The Vacuum-Tube Rectifier

Introduction

Although commercial power is distributed as ac, there are many devices that require dc. Electroplating and electrolytic refining of metals, charging of storage batteries, the operation of certain kinds of motors and of electronic circuits in radio and television all use direct current. In some cases the dc is provided by generators run by ac motors. In most cases, however, ac is converted to dc, or **rectified,** often by means of electron tubes. The purpose of this investigation is to allow you to become acquainted with the behavior of the vacuum-tube rectifier.

The basic principle that underlies the operation of electron tubes is that metallic surfaces, when heated, throw off (emit) some of their free electrons. For this emission to be continuous, however, two provisions must be made:

a) The emitting electrode must be connected to the negative terminal of a dc source so that the emitted electrons can be replaced.

b) The emitted electrons must be removed from the vicinity of the emitting electrode. This is done by placing a cold electrode near the hot emitting electrode and connecting it to the positive terminal of the same dc source. Emitted electrons are naturally attracted to it and then conducted away.

These connections are illustrated in Fig. 31–1. The emitting electrode is called the **cathode,** and the other is called the **anode,** or more commonly, the **plate.** Both electrodes are enclosed in a high vacuum or sometimes in a low-pressure gas. Because this tube contains two electrodes, it is called a **diode.**

Your problem is to experiment with this diode when an ac source is substituted for the B battery.

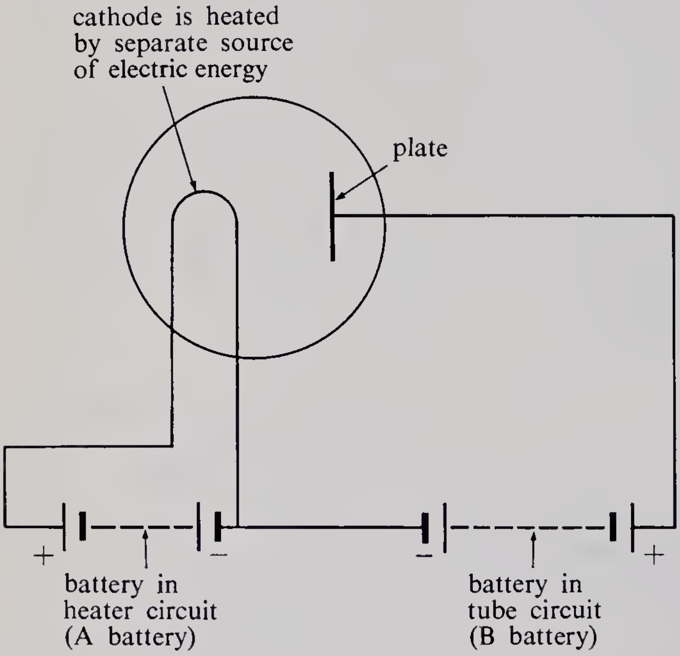


Fig. 31–1 This diagram summarizes the conditions necessary to maintain continuous electron emission.

Equipment

Circuit elements as indicated in Fig. 31–3 (See Step 1 for tube numbers); high-impedance dc voltmeters with test prods in ranges 0–500 V and 0–200 V; neon glow lamp and socket. *For Further Investigation:* oscilloscope; 5-microfarad (μF) or greater capacitor.

Procedure

STEP 1 Typical modern rectifier tubes include the 5Y3, 5U4, and 5T4. Terminal connections for these tubes are shown in Fig. 31–2. These diagrams are shown from the bottom view. Examine your tube and identify the connections.

STEP 2 Use one of these tubes to construct the simple rectifier circuit shown in Fig. 31–3. Note that it is supplied by a 120-volt ac line and that a 10,000-ohm resistor is in series with the tube circuit. Any electrons that flow through the tube must also flow through this resistor, called the **load.**

STEP 3 After your circuit has been checked by your instructor, close the switches and adjust the A-battery rheostat so that the cathode filament is supplied with a 5-V potential difference. Use a high-impedance dc voltmeter with about a 500-V range to determine the polarity of the potential difference to the load. Carefully apply the leads of the instrument across the load. If the meter deflects normally, the polarity is as indicated by the meter. If the meter deflects backwards, quickly remove it; in this case the polarity of the potential difference across the load is opposite to that indicated by the meter. Copy Fig. 31–3 and mark the ends of the load resistor + or – to indicate the polarity shown by the meter.

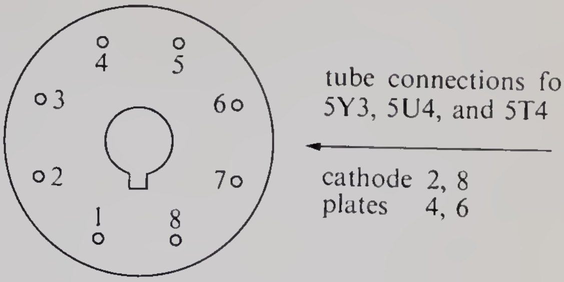


Fig. 31–2 Each of the tubes has two plates. For this investigation they should be connected together and used as one plate.

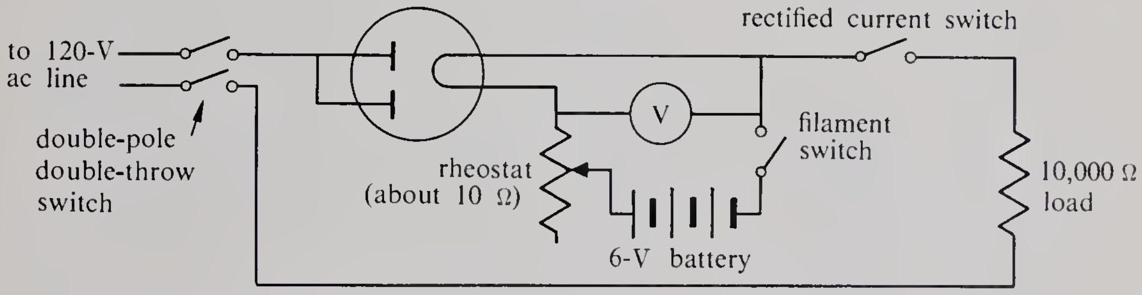


Fig. 31–3 This circuit is used to study the behavior of a rectifier.

STEP 4 Connect a neon-type glow lamp across the ac supply, and again across the load resistor. In which case does only one of the electrodes of this lamp appear to glow? In which case have you placed the lamp across a direct potential difference?

STEP 5 Connect a high-impedance voltmeter of 200-volts dc range across the load. What is the potential difference indicated by this instrument? Now observe the dc voltmeter across the load resistor carefully as you open the filament switch. Do you find that the potential difference drops to 0 at once or gradually? Reconnect the A battery and then open the ac supply switch as you watch the meter. What are the results?

Discussion

1. Is current in the load resistor ac or dc? How do you know?
2. Does the direction in which the electrons travel through the load agree with what was said in the introduction about the operation of the tube? Give reasons for your answer.
3. What must be the relative polarity of the cathode and the plate in order for the tube to pass a flow of electrons? In the circuit of Fig. 31–3 is this condition true all the time, half the time, or some other fraction of the time? Would you expect the current in the load to be a steady dc or an irregular dc? Give reasons for your answer.
4. Does the 6-V battery contribute any electrons to the tube circuit through the load, or does it serve only to heat the cathode? Explain, giving your evidence.
5. A diode rectifier is used in series with a 120-V ac supply line to provide charging current for a bank of storage batteries. Draw a diagram of the circuit, including the ac source, the diode with its cathode filament heating supply, and the batteries to be charged.
6. An experimenter wishes to use a diode in series with a dc meter to measure values in an ac circuit. Should the cathode terminal of the tube be connected to the positive terminal or the negative terminal of the meter movement? Why?
7. The half-wave rectifier of Fig. 31–3 is often called an ac-dc power supply because a radio or other device with this circuit may be used either with ac or dc. Explain how it must be connected in order to operate from a 120-V dc power line.
8. Many vacuum tubes have an indirectly heated cathode (Fig. 31–4). What is the advantage of this arrangement in a radio?

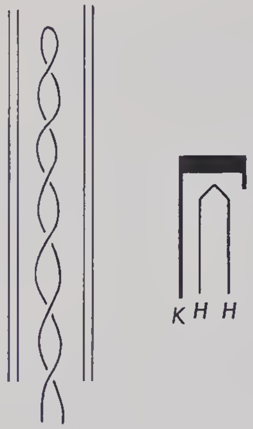


Fig. 31–4 This diagram shows the structure of an indirectly heated cathode. The heater (twisted wire) receives power from a separate source, usually alternating current, and is insulated from the surrounding cylindrical cathode. In the symbol for this type of cathode *K* stands for cathode and *H* for heater.

For Further Investigation

To be done only after the completion of Investigation 33, The Oscilloscope.

1. Use an oscilloscope to examine the wave form of the potential difference across the load resistor. Does your observation make the term "half-wave rectifier" seem appropriate? Now add a capacitor filter (5 μF or more), then an L filter, then a pi-filter (Fig. 31–5). Make drawings to show the wave form in each case. What is the purpose of a filter in a rectifier circuit?

2. Follow a standard diagram and make a full-wave rectifier. What additional parts are needed? Examine the wave form with an oscilloscope with and without the filters of Fig. 31–5. Compare the results with those for the half-wave rectifier.

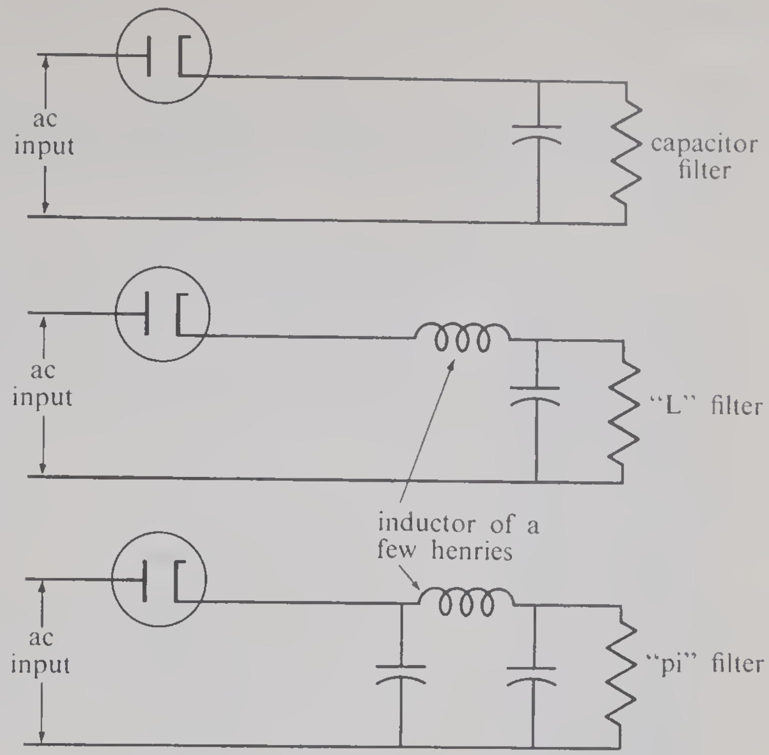


Fig. 31–5 These diagrams show how filters are connected in a rectifier circuit. For simplicity, the circuit that heats the cathode has been omitted.

INVESTIGATION

32

The Three-Electrode Vacuum Tube

Introduction

The diode tube changes ac to dc by permitting electrons to flow in one direction and by preventing them from flowing in the opposite direction. Many applications of electronics, however, require that not only the direction, but also the magnitude of electron flow be controlled—a control that becomes possible when a third electrode is added to the tube, which is then called a **triode.**

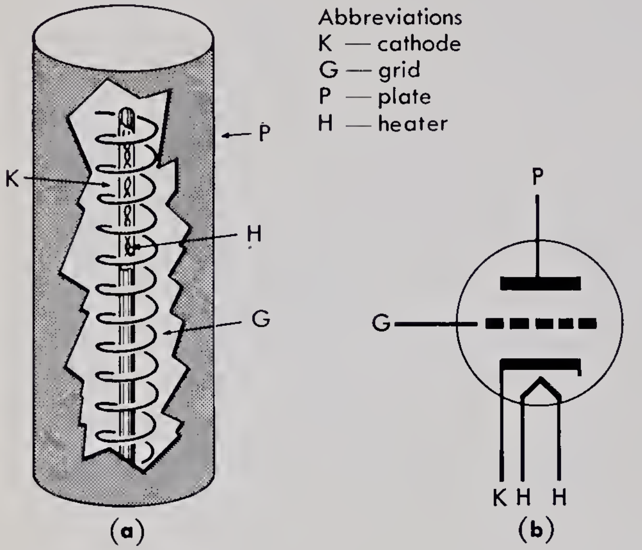
In this investigation you will observe the behavior of a triode, particularly its behavior as an amplifier.

Equipment

The equipment is shown in Fig. 32–2 for Part A and Fig. 32–3 for Part B.

Procedure

The structure of a triode is shown in Fig. 32–1. The third electrode, called the grid, is made of an open mesh or a loosely wound spiral and is placed between the cathode and the plate, quite close to the cathode. Figure 32–2 shows how such a tube may be connected in a circuit.



(a) (b)

Fig. 32–1 **a.** Diagram of a typical triode, showing the cathode (thin central cylinder), grid (spiral wire), and plate (outer cylinder). In an actual tube all of this is encased in a glass or metal envelope. Note that the grid is much closer to the cathode than is the plate. Consequently, the grid potential has more influence on current through the tube than has the plate potential. **b.** Symbol used for a triode.

Before you start your investigation, determine for yourself some of the behavior of such a tube by answering the following questions based on Fig. 32–2:

a) At the start the grid is at the same potential as the cathode. (This can be accomplished by moving the contact of the grid rheostat all the way to the right in the diagram.) The plate is positive with respect to the cathode. The grid is mostly empty space, therefore, electrons can readily pass through it. In what direction will electrons move in the tube?

b) Now suppose the plate-to-cathode potential difference (V_p) is increased (by moving the contact of the plate rheostat to the right in the diagram), making the plate more positive. What should happen to the plate current (I_p) registered by the ammeter?

c) Now suppose the grid is made very slightly negative with respect to the cathode. It is then said to have a negative **grid bias** (V_g). How does this affect the plate current?

d) With a negative grid bias, would you expect that there would be current in the grid circuit?

e) As the negative grid bias is increased, what would you expect to happen to the plate current (I_p)?

f) What two changes in the circuit can cause changes in the plate current?

g) Which would you expect to produce a greater change in the plate current, a change of 10 V in V_g or a change of 10 V in V_p? Why?

h) Now suppose the grid is a bit negative (perhaps −4 V), but not negative enough to stop the plate current. You insert into the grid circuit a phonograph pickup that generates a very tiny alternating emf (less than 1 V), having the frequency of the sound recorded on the record disk. If the frequency of the sound was 500 cycles per second, what would happen to the plate current?

In Part A of this investigation you will test the accuracy of your answers to Questions (b) to (g); in Part B you will explore the possibilities indicated by your answer to Question (h).

A. FACTORS THAT INFLUENCE THE SIZE OF THE PLATE CURRENT OF A TRIODE

STEP 1 Set up the circuit shown in Fig. 32–2. Instead of batteries, you may be given variable dc power supply units that plug into the ac outlet. These are rectifiers similar to the one you studied in Investigation 31, although they may contain a different type of diode.

STEP 2 Try each of the circuit changes indicated in Questions (a)-(g) above and record your observations on a suitable data sheet.

STEP 3 With the grid bias set at -8 V, adjust V_p until I_p is 10 mA. Now change V_g to -6 V, a change of 2 volts in the grid bias. What happens to I_p? How much must you now change V_p in order to bring the plate current back to 10 mA? Record this information on your data sheet.

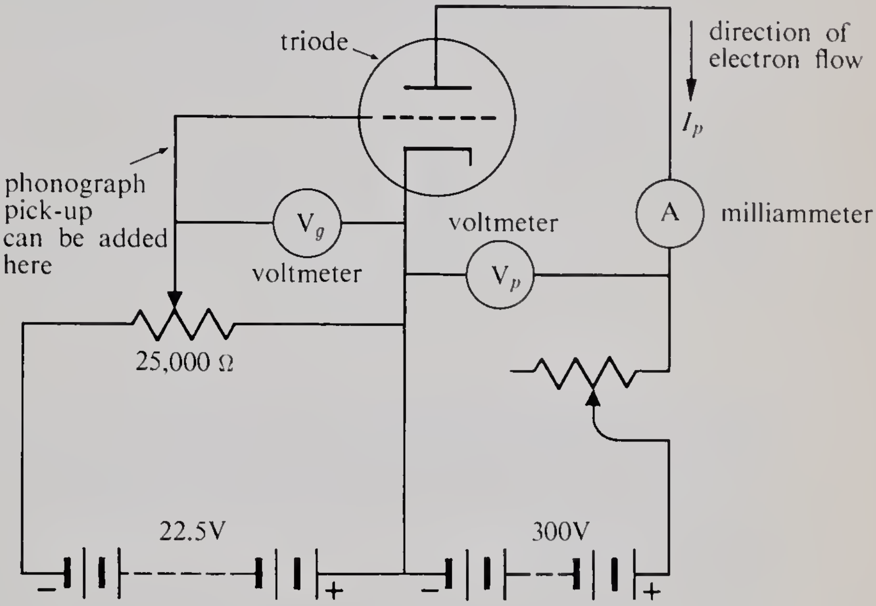


Fig. 32–2 This circuit makes it possible to study the control characteristics of a triode grid. The heater connections to the cathode are not shown.

Discussion

1. When V_p is increased, what is the effect on the plate current?
2. As the negative grid bias is slowly increased, what is the effect on the plate current? Is there a cut-off point?
3. Which has more effect on the plate current, a small change in grid bias or a change of the same size in V_p? What is your evidence?
4. The amplification factor of a tube may be defined thus:

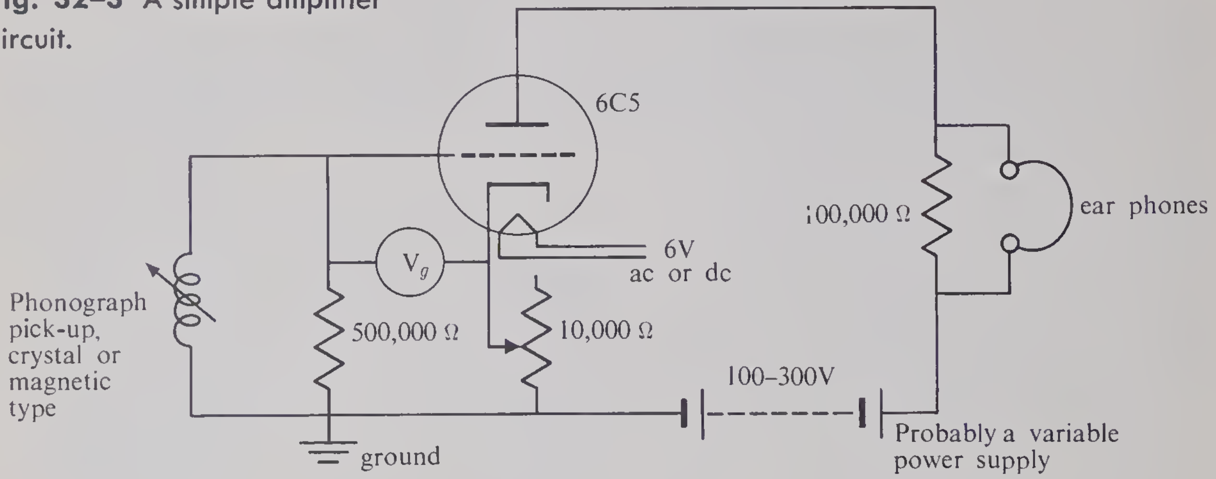
$$\mu \text{ (mu)} = \frac{\text{the change in } V_p \text{ that produces a certain change in } I_p}{\text{the change in } V_g \text{ that reverses the change in } I_p}.$$

What is the amplification factor for your tube? Show your method on the data sheet.

B. THE TRIODE AS AN AMPLIFIER

STEP 1 Use your tube in the simple amplifier circuit shown in Fig. 32–3. Adjust the resistor in the cathode circuit so that V_g is -8 V. What is the approximate size of the cathode resistor for this adjustment?

Fig. 32–3 A simple amplifier circuit.


6C5
100,000 Ω
ear phones
V_g
6V
ac or dc
Phonograph pick-up, crystal or magnetic type
500,000 Ω
10,000 Ω
100–300V
ground
Probably a variable power supply

STEP 2 Now place the phonograph pickup needle on a spinning phonograph record and note the results in the earphones. Disconnect the earphones and place them directly across the terminals of the phonograph pickup. What difference do you note in the volume of the sound produced?

STEP 3 Replace the earphones in the output circuit of the amplifier. Now adjust the cathode resistor so that V_g is 0. How does the output now sound?

STEP 4 Adjust V_g to 20–30 V (this will require a cathode resistor greater than 10 K). Now how does the output sound?

STEP 5 Listen to a phonograph record through your amplifier and while listening, place an electrolytic capacitor in parallel with the cathode resistor, connecting the negative end of the capacitor to ground and its positive end to the cathode itself. What difference do you notice in the sound produced in the earphones?

STEP 6 While you are listening to the amplifier, disconnect the leads to the tube heater. Does the sound in the earphones cease immediately or gradually?

Discussion

1. Does the circuit of Fig. 31–3 amplify the signal from the phonograph pickup? What is your evidence?
2. What are some of the factors that influence the ability of the circuit to produce a satisfactory amplified output signal? Under what conditions did this circuit operate best?
3. How do you account for the behavior noticed in Steps 5 and 6?

4. Why is it not necessary to have a direct electrical connection between the heater and the cathode of the tube in Figs. 32–2 and 32–3?
5. What is the source of the energy that comes from the earphones as sound energy when the earphones are connected as in Fig. 32–3? Does any of this output energy come from the phonograph pickup?
6. What is the source of the energy of the signal put out by the phonograph pickup?
7. Is it more correct to say that a triode makes a small signal larger, or that it permits a small energy source to control a larger one? Give reasons for your answer.
8. Why is it undesirable for the grid bias of an amplifier tube to be positive?
9. Why does it take a half minute or more for the average household radio to play after the switch is turned on? Why does a transistor radio not have this delay?

INVESTIGATION

33

The Oscilloscope

Introduction

If you did Investigation 19 in "Fundamentals of Physics" (Characteristics of Musical Sound), you are already familiar with the oscilloscope. In that investigation the oscilloscope graphed the wave form of various musical sounds. While that use of the oscilloscope is interesting, this instrument is more widely used as a tool in electronics. As you perform this experiment, you will learn something of the ways in which an oscilloscope can be used.

The heart of an oscilloscope is a cathode-ray tube (Fig. 33–1). The tube contains a cathode especially designed to emit electrons in one particular direction. It has one or more anodes which attract electrons. Each anode is a cylinder with a hole at one end. Electrons coming at great speeds down the axes of the cylinders, shoot through the holes and strike the end of the tube, making a glowing spot on the fluorescent material painted there. Between the cathode and anode is a grid that controls the intensity of the beam. The cathode, anode, and grid make up what is called the **electron gun** of the tube.

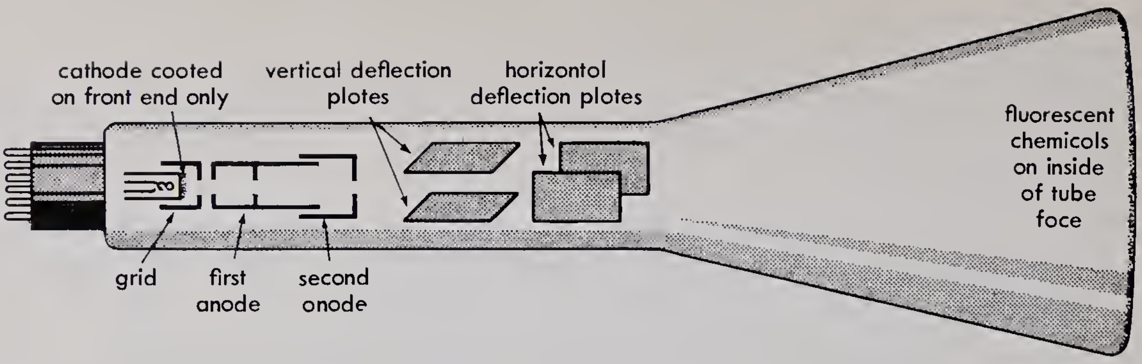

cathode coated on front end only
vertical deflection plates
horizontal deflection plates
fluorescent chemicals on inside of tube face
grid
first anode
second anode

Fig. 33–1 This is a simplified diagram of a cathode-ray tube, as used in oscilloscopes. The inside of the tube is coated with a thin layer of carbon so that electrons that strike the tube face leak back to the positive terminal of the power supply.

So far the tube is not very different from a triode, except for the glowing screen. However, the cathode-ray tube also has two pairs of deflection plates, as you can see in the diagram. Imagine a stream of electrons moving rapidly between the two plates that are set horizontally in the tube. If the upper plate is positive and the lower one negative, the stream will be deflected toward the upper plate. The spot on the end of the tube will shift upward. Now if the polarity of the plates is reversed, the spot shifts downward. These plates are called **vertical deflection plates** (the plates are horizontal, but the deflection they produce is vertical). The other pair of plates works in the same way, but causes the spot to move horizontally; they are called **horizontal deflection plates.**

As you operate the oscilloscope, try to understand its behavior in terms of the structure described above.

Equipment

Cathode ray oscilloscope; doorbell transformer; rheostat (or potentiometer); ac voltmeter.

Procedure

STEP 1 Examine the knobs and dials on the instrument and locate the following: **a)** on and off switch or switches; **b)** controls for position of horizontal and vertical deflections; **c)** controls for amplitude of horizontal and vertical deflections (gain controls); **d)** focus and intensity controls; **e)** sweep circuit (or linear time base) controls; **f)** a switch that determines whether the sweep circuit is used or not; **g)** vertical-axis input terminals; horizontal-axis input terminals.

STEP 2 Turn power on. Turn sweep circuit on. If you do not see a light on the screen in a few seconds, turn the intensity knob until you do. **Never permit a stationary spot to remain on the screen, as this will damage the screen. If such a spot occurs, turn the intensity knob down or widen the spot to a line with one of the gain controls.** Use the horizontal gain control to make the beam almost as wide as the screen. Use the two position controls to center it. Focus the beam.

STEP 3 Find the sweep-control knob that regulates the frequency of the sweep and make the frequency as low as possible. You will see a single dot moving across the screen from left to right. It then moves back from right to left, but too fast for you to see it go. During its left-to-right trip, does the spot appear to move with uniform speed or nonuniform speed? If you were unable to slow the spot sufficiently for this observation, record that fact in your *Data Book*.

STEP 4 Increase the sweep frequency to 20 or more sweeps per second. What do you see?

STEP 5 Suppose that you have adjusted the sweep oscillator so that the dot moves across the screen in a tenth of a second. Now imagine that you have connected a varying potential difference across the vertical deflection plates, one that makes the upper plate positive once every 0.01 sec. What effect will this have on the position of the dot as it travels once across the tube? Will it produce the same effect on the second trip across, or will it be different? Be sure you understand the answers to these questions before you proceed.

STEP 6 Connect the low-voltage side of a transformer to the vertical-input terminal and ground. Plug the transformer into the ac outlet. Adjust the sweep circuit frequency and the vertical-gain control until you have exactly one sine curve cycle on the screen. When you have done this, what is the frequency of the sweep oscillator?

Readjust for two and for three cycles. What are the sweep frequencies in these cases?

What kind of pattern do you expect on the screen for a sweep frequency of 120 cycles per second? Attempt to obtain this pattern and show it to the instructor.

STEP 7 Readjust the sweep to show one complete sine wave. Disconnect the transformer. Attach a lead wire to the vertical-input terminal (*not to the ground*) and hold the other end in your hand. What do you observe?

STEP 8 Turn off the sweep circuit oscillator and connect a second low-voltage transformer to the horizontal input terminal and ground. Draw the patterns you see on the screen as you move the vertical gain control. These patterns are typical of the two ac's that are of the same frequency and in phase with each other.

STEP 9 With a rheostat (or potentiometer) and transformer, set up a variable voltage across the vertical input terminals of the oscilloscope (Fig. 33–2). Reduce the horizontal deflection to 0. On a data sheet record the length of the line on the oscilloscope for various values of *V*.

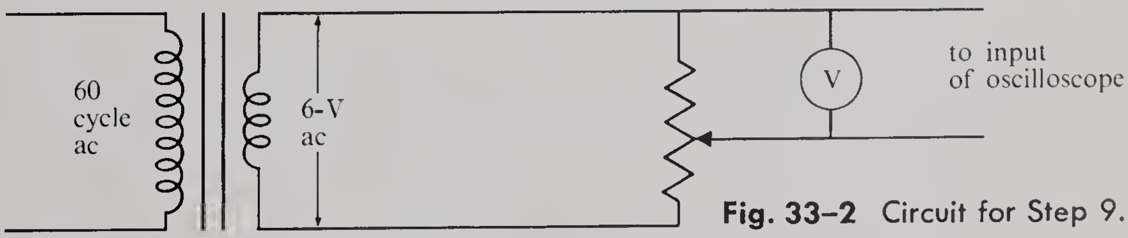


Fig. 33–2 Circuit for Step 9.

Discussion

1. The motion you observed in Step 3 is controlled by a changing potential difference between the horizontal deflection plates. What kind of change in potential difference between these plates will produce the kind of motion you observed?

2. Account for the appearance of the oscilloscope screen in Step 4.
3. How might an oscilloscope be used to detect the frequency of an alternating voltage?
4. Account for the observation made in Step 7.
5. How might an oscilloscope be used as a voltmeter? How might you make the voltmeter very sensitive?
6. In order for the scope to make a sine-wave graph of an ac, why must you use the sweep circuit for the horizontal deflection?
7. In order to show clearly the wave form of a signal, what adjustments do you have to make in the sweep circuit?

For Further Investigation

1. Follow the suggestions described in Investigation 31 under the section *For Further Investigation.*
2. Use a transformer on the horizontal input and a variable-frequency oscillator on the vertical input. Study and sketch the patterns when the ratio of the two frequencies is 1:1; 2:1; 3:1; 3:2, etc. These are called *Lissajous figures.*
3. The equation for the ac on the vertical axis of the scope may be written as $y = A \sin \theta$ where A is the amplitude and θ is the phase angle. If you have on the horizontal axis an ac with the same frequency as the ac on the vertical axis and in phase with the first ac, its equation is $x = B \sin \theta$. Prove that a combination of these two should produce a straight line.

   If the horizontal ac is 90° out of phase with the vertical one, but both have the same frequency, its equation is $x = B \cos \theta$. Prove that this combination should produce a circle when $A = B$, and an ellipse when $A \neq B$.

APPENDIX I

Scientific Notation

Scientific notation simplifies the writing of numbers by using powers of 10. For example:

$$1000 = 10 \cdot 10 \cdot 10 = 10^3$$
$$1{,}000{,}000{,}000{,}000{,}000 = 10^{15}$$

Now suppose you wish to write 6,147,300,000 in this way. You could write:

$$61{,}473 \times 100{,}000 = 61{,}473 \times 10^5$$

or

$$6.1473 \times 1{,}000{,}000{,}000 = 6.1473 \times 10^9$$

Notice that the exponent 5, in the first case, is the number of places that the decimal point was moved to the *left* in 6,147,300,000 to arrive at 61,473. Similarly, the decimal point was moved 9 places to the left in the second case. Both of these ways of writing the large number are correct, but the second form is usually preferred.

Very small numbers can be handled similarly:

$$\begin{aligned} 0.00043278 &= \frac{4.3278}{10000} \\ &= \frac{4.3278}{10^4} = 4.3278 \times 10^{-4} \end{aligned}$$

Here the exponent equals the number of places the decimal point was moved to the *right*.

Try performing the following operations:

$$\frac{6{,}130{,}000{,}000{,}000 \times 0.000000374 \times 45}{2{,}700{,}000{,}000 \times 0.00000000034 \times 2300} = ?$$

First, simplify by writing each factor in scientific notation.

$$\frac{6.13 \times 10^{12} \times 3.74 \times 10^{-7} \times 4.5 \times 10^1}{2.7 \times 10^9 \times 3.4 \times 10^{-10} \times 2.3 \times 10^3} = ?$$

Now gather like factors and combine.

$$\frac{6.13 \times 3.74 \times 4.5 \times 10^{12} \times 10^{-7} \times 10^1}{2.7 \times 3.4 \times 2.3 \times 10^9 \times 10^{-10} \times 10^3} = \frac{6.13 \times 3.74 \times 4.5 \times 10^4}{2.7 \times 3.4 \times 2.3}.$$

In this way there is no wasted effort, and the arithmetic is much simpler. You may, of course, use either slide rule or logarithms when you have reduced the expression to the last step.

Practice Problems

1. Simplify each of the following:

(a) a^2a^3 (b) $\frac{a^3}{a^2}$ (c) $\frac{a^2}{a^3}$ (d) $\frac{a^3b^2c^5}{ab^4c^2}$

(e) $2 \times 10^2 \times 6 \times 10^{-3} \times 3 \times 10^4$ (f) $\dfrac{3 \times 10^2 \times 14 \times 10^3}{7 \times 10^4 \times 10^5}$

2. Write in scientific notation:
   (a) 141,000 (b) 0.073 (c) 0.00013500
   (d) 48,160,000,000 (e) 2,000,000 (f) 0.015903

3. Set up in scientific notation and solve:
   (a) A light year is 186,000 × 3600 × 24 × 365 miles
   (b) The number of wavelengths of red light in 1 inch is

$$\frac{1}{0.00000065 \times 39.37}$$

   (c) The wavelength of a station broadcasting at 1340 kilocycles is

$$\frac{300{,}000{,}000}{1{,}340{,}000} \text{ meters}$$

APPENDIX 2

Significant Digits

On page L6 of Investigation 2, you find the rule: *Record all the digits of which you are certain, plus one that you estimate.* Suppose that you measure the length of a table with a meter stick and find that it lies between 158.6 cm and 158.7 cm. You estimate that the end of the table is 3/10ths of the way between two of the millimeter marks, and therefore record the length as 158.63 cm. Your measurement is said to have five significant digits, the last of which is a *doubtful digit.*

The position of the decimal point in a number has nothing to do with the number of significant digits. For example, 256, 3.50, and 0.00215 all have three significant digits. The 0 in the second number tells you that the measurement is more likely to be 3.50 than 3.49 or 3.51. The 0's in 0.00215 merely locate the decimal point.

If the recorded number is 21,000, you cannot tell by inspection whether there are as many as five significant digits or as few as two. In such a case, the number should be written in scientific notation: 2.10×10^4 means that there are three significant digits, whereas 2.1×10^4 means that there are only two.

Practice Problems

1. Copy each of the following numbers, circle the doubtful digit, and record the number of significant digits:

3.472 0.59 2,687.62 2.00×10^6
14.00 0.006 981 2.08×10^3

2. The length of a building is found to be 3000 cm. Express the number in such a form that a reader will know that there are three significant digits.
3. The population of a city is 7,000,000. Express this so that a reader will know that there is only one significant digit in the number.

The rules for computations based on measured quantities are:

RULE 1 If you are adding or subtracting, disregard all digits to the right of the first doubtful digit used in the operation. Examples:

$$\begin{array}{lrr} 6.703 & 6.70 & 4.4810 \\ 2.49 & 2.49 & 1.3000 \\ 1.7368 & 1.74 & 9.0738 \\ \hline & 10.93 & 14.8548 \end{array}$$

The fact that the 2.49 in the column at the left stops at the 9 tells you that the 9 is a doubtful digit and that it is nonsense to put 0's after it when you add the column. Therefore the other numbers must be shortened by rounding off, as shown in the middle column, before the addition takes place. The 0's in the column at the right tell you that all of these numbers have four significant digits after the decimal point. Therefore all the digits can be used in the addition.

RULE 2 If you are multiplying or dividing, in most cases record in the answer as many significant digits as there are in the least reliable number in the data. For example:

$521.8 \times 0.0629 = 32.82122$ if you multiply it all the way.

521.8 has four significant digits, whereas 0.0629 has three. Therefore the answer is rounded off to three significant digits and is given as 32.8. The reason for rounding off can be shown by working out the problem above, showing doubtful digits in italics:

$$\begin{array}{r} 521.\mathit{8} \\ \times 0.062\mathit{9} \\ \hline \mathit{46962} \\ 1043\mathit{6} \\ 3130\mathit{8} \\ \hline 32.\mathit{82122} \end{array}$$

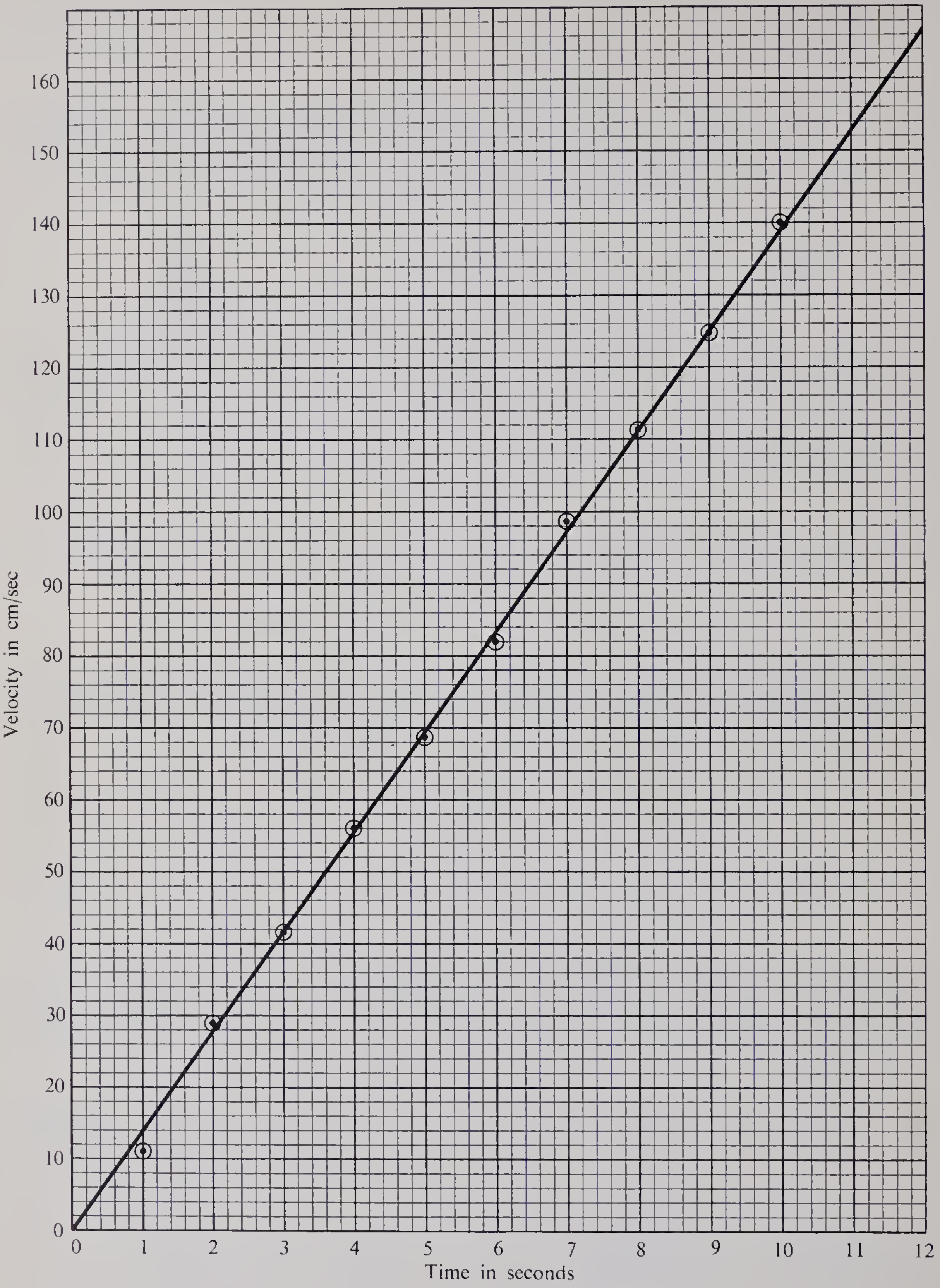
All of the digits in *46962* are doubtful, because they are obtained by multiplying by the doubtful digit, 9. As a result, five of the digits in the answer are doubtful, and only the first of these doubtful digits, the 8, has any meaning at all.

Practice Problems

Round off the answer in each of the following cases to the proper number of significant digits:

1. $4.11 \times 0.23 = 0.9453$
2. $0.015 \times 346 \times 5142 = 26686.98$
3. $4.700 \div 156 = 0.030128$

Rules for Graphing Experimental Data



Velocity-time graph for a ball rolling down a slope.

These rules are illustrated by the velocity-time graph at the left.

RULE 1 Decide which variable is independent and which one is dependent. For the graph shown, time is considered to be the independent variable because the velocity depends on how long the ball has been rolling. The independent variable is to be graphed on the horizontal axis and the dependent one on the vertical axis.

RULE 2 Choose scales that will stretch the variables across the page, using as much of the graph paper as possible. However, when you do this, choose a scale that makes it easy to locate points. Never let 5 squares equal 6 units, for example. A scale having 5 squares equal to 10 units would be better. It is not necessary to use the same scale in both directions, even when both variables are expressed in the same unit (both in meters, for example).

RULE 3 Put numbers on the axes, and labels along the sides, which tell what quantity is being graphed and which name the unit being measured.

RULE 4 Locate each data point by making a small dot in pencil. When you are sure that you have made no mistake in locating the points, ink in each dot and draw a circle around it in ink.

RULE 5 In pencil, draw the smooth line that you think fits the data points best. If the points seem to lie along a straight line, draw the line of best fit with a ruler, preferably a transparent one, so you can see all of the points while you select the position of the line. If the points seem to lie along a curve, draw a smooth curve. Do not try to force your line to go through all the points.

Experimental error will usually cause some of the points to be off the line. For an experiment done carefully, with very accurate equipment, the points may be very close to the line. Because you have located the data points with ink and your line in pencil, you will find it easy to change the line if you are not satisfied with it. Later you can draw the line in ink also. However, often an ink line is not as satisfactory as a pencil line because it may smudge.

Sometimes you will know that one of your points has no experimental error and that the line must therefore go through that point. Such is the case with the graph shown here. If a ball starts from rest to roll down a slope, then when $t = 0$, the velocity must also be 0.

RULE 6 Give your graph a title.

APPENDIX 4

Percent of Error

Percent of error in a measurement is defined as:

$$\frac{\text{difference between measured value and correct value}}{\text{correct value}} \times 100$$

The "correct value" may be the value considered by experts to be the best measurement that has been made. The Physical Constants given in the Appendix are such "best" values.

In some cases (when you are using a meter stick) the correct value is considered to be a distance marked on the stick, and you estimate the maximum possible error you might make when you use the stick. If the stick is marked in mm, you might think that the maximum possible error is 0.5 mm. Then you estimate the percent of error as:

$$\frac{\text{estimated maximum error}}{\text{correct value}} \times 100$$

In the case of the meter stick, if you are measuring something that is 1 m long (1000 mm), the estimated percent of error is:

$$\frac{0.5\text{ mm}}{1000\text{ mm}} \times 100 = 0.05\%$$

However, if you are measuring something that is 1 cm long (10 mm), the estimated percent of error is:

$$\frac{0.5\text{ mm}}{10\text{ mm}} \times 100 = 5\%$$

Often you have no "best" values for comparison when you make measurements in the laboratory. If you have made two measurements of the same quantity, you may wish to calculate the percent of difference between them. In that case, you use the formula:

$$\text{percent of difference} = \frac{\text{difference between the measurements}}{\text{average of the measurements}} \times 100$$

Practice Problems

1. The speed of light is measured by a student as 2.8×10^8 m/sec. What is his percent of error?
2. Millikan, who first measured the charge on the electron, reported a value of 1.59×10^{-19}C. It was later found that this was incorrect because of an error in one of the constants, measured by other people, which he had used in his calculations. What was the percent of error?
3. If you estimate a maximum possible error of 0.5 g when you use a certain balance for weighing, what is the percent of error when the object has a weight of (a) 2 kg? (b) 800 g? (c) 20 g?
4. Two measurements of the index of refraction of a piece of glass are 1.593 and 1.598. What is the percent of difference?

APPENDIX 5

The Metric System

Two metric systems are in common use, the MKS (meter-kilogram-second) and the CGS (centimeter-gram-second). The fundamental units in these systems are those of length, mass, and time. Prefixes are used to indicate multiples or fractions of units. Hence, one thousand meters is called a *kilo*meter, and one thousandth of a meter is a *milli*meter.

Multiple or Fraction	*Prefix*	*Symbol*
10^6	mega-	M
10^3	kilo-	k
10^{-2}	centi-	c
10^{-3}	milli-	m
10^{-6}	micro-	μ (mu)
10^{-9}	nano-	n
10^{-12}	pico-	p*

*A common unit of electric capacitance is the picofarad, 10^{-12} F.

LENGTH

Fundamental unit: the **meter (m)** is defined as a multiple of the wavelength of the orange-red light from krypton-86.

Unit	*Abbreviation*	*Equivalent*
kilometer	km	10^3 m
centimeter	cm	10^{-2} m
millimeter	mm	10^{-3} m
micron*	μ	10^{-6} m
millimicron*	mμ	10^{-9} m
Angstrom	A	10^{-10} m

*"Micron" and "millimicron" are names not using the system of prefixes; otherwise they would be *micrometer* and *nanometer*.

1 meter = 39.37 in. = 3.281 ft

1 mile = 1609 m = 1.609 km

1 foot = 0.3048 m

1 in. = 2.54 cm

MASS

Fundamental unit: the **kilogram (kg)** is defined as the mass of a cylinder of platinum-iridium kept at the International Bureau of Weights and Measures, in Sèvres, France.

Unit	*Abbreviation*	*Equivalent*
kilogram	kg	10^3 g
milligram	mg	10^{-3} g
microgram	μg	10^{-6} g

1 kilogram = 2.20 lb

1 lb = 0.454 kg

VOLUME

Some units are based on the length unit. Another unit is the **liter (l)**, defined as the volume occupied by 1 kg of water at 4°C and 760 mm pressure.

Unit	*Abbreviation*	*Equivalent*
cubic centimeter	cm^3	10^{-6} m^3
cubic millimeter	mm^3	10^{-9} m^3
milliliter	ml*	10^{-3} l
microliter	μl	10^{-6} l

*1 liter = 1000.028 cm^3. Therefore 1 ml is almost exactly equal to 1 cm^3.

TIME

Fundamental unit: the **second (sec)** is defined as a multiple of the transition frequency of the cesium atom.

Unit	*Abbreviation*	*Equivalent*
millisecond	msec	10^{-3} sec
microsecond	μsec	10^{-6} sec
nanosecond	nsec	10^{-9} sec

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7–2 Screwdriver and hammer: Courtesy of Snap-on Tools Corp. Can opener and egg beater: Courtesy of EKCO Products Company

7–3 Courtesy of Professor Ernest Rabinowics, photograph taken by Professor N. H. Cook, Massachusetts Institute of Technology

7–22 Courtesy of Upson-Walton Company

8–1a Courtesy of American Export and Isbrandtsen Lines

8–1b Courtesy of The Boeing Company

8–10 Courtesy of Salt Lake City Chamber of Commerce

8–11b Courtesy of Thermometer Corporation of America

8–12 Official U.S. Navy Photograph

8–15b Courtesy of Arthur H. Thomas Company

8–16 Cioffero, Fundamental Photographs

9–1 Cioffero, Fundamental Photographs

9–2 Cioffero, Fundamental Photographs

9–4 Cioffero, Fundamental Photographs

9–5 Cioffero, Fundamental Photographs

9–8 Courtesy of Bell Telephone Laboratories, Inc.

9–9 Courtesy of Bell Telephone Laboratories, Inc.

9–15 Isogonic Chart: Courtesy of U.S. Coast and Geodetic Survey

13–17d Courtesy of General Electric Company

Page 351 Culver Pictures, Inc.

16–12 Courtesy of Lawrence Radiation Laboratory, University of California

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